The Effects of Multi-channel Visible Spectrum Imaging on Perceived Spatial Image Quality and Color Reproduction Accuracy

Ellen A. Day

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The Effects of Multi-channel Visible Spectrum Imaging on Perceived Spatial Image Quality and Color Reproduction Accuracy

Ellen A. Day

B.S. Rochester Institute of Technology (2000)

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Color Science in the Center for Imaging Science, Rochester Institute of Technology

April 2003

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Accepted by Dr. Roy S. Berns, Coordinator, M.S. Degree Program
TITLE OF THESIS
The Effects of Multi-channel Visible Spectrum Imaging on Perceived Spatial Image Quality and Color Reproduction Accuracy

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5/21/03
THE EFFECTS OF MULTI-CHANNEL VISIBLE SPECTRUM IMAGING ON PERCEIVED SPATIAL IMAGE QUALITY AND COLOR REPRODUCTION ACCURACY

Ellen A. Day

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Color Science in the Center for Imaging Science, Rochester Institute of Technology

ABSTRACT

Two paired-comparison psychophysical experiments were performed. The stimuli consisted of six image types resulting from several multispectral image-capture and reconstruction techniques. A seventh image type, color-managed images from a high-end consumer camera, was also included in the first experiment to compare the accuracy of commercial RGB imaging. The images were evaluated under simulated daylight (6800K) and incandescent (2700K) illumination. The first experiment evaluated color reproduction accuracy. Under simulated daylight, the subjects judged all of the images to have the same color accuracy, except the consumer camera image which was significantly worse. Under incandescent illumination, all the images, including the consumer camera, had equivalent performance. The second experiment evaluated image quality. The results of this experiment were highly target dependent. A subsequent image registration experiment showed that the results of the image quality experiment were affected by image registration to some degree. An analysis of the color reproduction accuracy and image quality experiments combined showed that the consumer camera image type was preferred the least overall. The most preferred image types were the thirty-one-channel image type and both six-channel image types created using RGB filters along with a Wratten filter, with eigenvector analysis and pseudo-inverse transformations.
The Colors Live
by Mary O'Neill

The colors live
Between black and white
In a land that we
Know best by sight.
But knowing best
Isn't everything,
For colors dance
And colors sing,
And colors laugh
And colors cry-
Turn off the light
And colors die.
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INTRODUCTION

The degree of quality for digital imaging is application dependent. Some applications of digital imaging do not require reproductions that have perfect color or spatial image quality. Most purposes in business and industry do not require such accuracy. For example, it is not important to be able to see the actual shade of red of the bricks on a contractor’s documentation of the construction of a building, as long as the stage of the building process is obvious. Most family vacation photographs also do not require high accuracy.

Some applications of digital imaging require higher quality imaging. In many cases, for example, there is great importance to the accurate color reproduction of artwork. Digital imaging of artwork is often used for conservation, preservation, and restoration. Artwork does not last forever. It may be damaged, fade over time, or just deteriorate. It is important to have accurate reproductions of artwork not only for conservation, preservation, and restoration, but also for historical purposes, after the piece has long since deteriorated into nothing.

Many consumer digital cameras do not have the capability of creating such high quality reproductions. This is true both in terms of color accuracy and image quality. Most digital cameras consist of only three channels (red, green, and blue) and a CCD or CMOS sensor. For most consumer imaging applications, the level of quality achieved by these cameras is more than acceptable and is often imperceptible to the untrained observer. One specific problem is that traditional three-channel imaging creates reproductions that are, at best, metameric to the original. The reproduction will look different under different light sources compared to the
original. This problem can be avoided, in principle, by the use of multispectral imaging, or multi-channel visible spectrum imaging (MVSI).

Multispectral imaging involves using more than three channels to capture an image. The optimal number of channels used can vary and may depend on many factors such as the imaging system, the subject or scene, and the technique for reconstructing the image. In addition, the costs and benefits of using more or fewer channels must be considered for each specific application. Similar considerations must be taken into account when considering reconstruction techniques.

The goal of this research is to evaluate the spectral capture and reconstruction techniques that are being developed at the Munsell Color Science Laboratory. The results from this research will be applied to an imaging system currently being produced in the Spectral Color Imaging Laboratory at MCSL as part of the Art Spectral Imaging (Art-SI) project. This imaging system will eventually be used in various museum settings, specifically at the National Gallery of Art in Washington D.C. and the Museum of Modern Art in New York City.

It is hypothesized that different methods of MVSI may lead to artifacts or errors that affect the quality of the reproductions of captured images. These artifacts and errors may be colorimetric or spatial in nature. In this thesis, the hypothesis is discussed, experiments are presented, and results are revealed. First, concepts relating to both digital imaging and multispectral imaging are expanded upon and other research relating to this thesis is discussed.
2 BACKGROUND

2.1 Digitizing Images

Digital imaging has become increasingly important in the past several years. It is recognized as a way to store, catalogue, analyze, manipulate, and archive information. This is often important for documents, images, and works of art. Our discussion will mainly be concerned with artwork since the final application of this research will be in museum settings. An advantage of digital imaging for the reproduction of artwork is that digital files will not age or lose their color with time, as film will inevitably do (Burmeister, 1996). There are two main purposes of image digitization that can be considered for artwork. The first is producing images that will be used for presentation and should be aesthetically pleasing. Secondly, accurate image reproduction is necessary for historic and scientific purposes. The latter approach will be discussed throughout this thesis.

For artwork, a primary concern is conservation of the original piece. This is true whether we are talking about art at a gallery or museum, or even a personal collection of an artist’s own work. The process of digitizing works of art must be performed with great care and concern for the original object. Therefore, the process usually takes a great deal of time, energy, planning, and in the case of professional galleries and museums, manpower.

One of the most difficult tasks in acquiring digital images of artwork is the concern for the safety of the piece. While this includes security of the painting from being stolen, a greater concern is for its physical well-being. It has been stated that one of the most destructive things to happen to a fragile object is the physical handling of it (Chapman, 1999). This is especially true for very
large or delicate artwork or paintings with very heavy frames (Burmeister, 1996). Since a great deal of care must be taken, many people are usually involved in transporting and setting up a piece of artwork. Usually, in the case of digital photography, a studio must be completely ready before the artwork even enters. This includes obtaining a studio or other place to capture the image, setting it up, and arranging to have the piece brought there. Setting up the studio includes placement of the easel (or other place to put the subject), lighting decisions, and camera decisions.

The first question that must be asked is “what will the digital image be used for?” Besser (1991) asks the more specific question: “Will these images be used merely for recognition purposes or will they also be used for study or analysis?” After the answers to these questions are known, it will be possible to determine how to go about digitizing the images.

In the case of artwork, digital-image processing is often used for conservation, preservation, and restoration (Besser, 1991). Specifically, there are at least three instances in which this type of work is performed. First, “condition reporting” is often used in museums and galleries to track the wear and tear of a work of art (Besser, 1991). The National Gallery in London began a project to do just this. The VASARI project (Visual Arts System for Archiving and Retrieval of Images) began in the early 1990’s to form an archive to compare future measurements in color and surface appearance with current ones (Saunders, 1993). Using this information, the deterioration of a work of art can be followed. Second, digital imaging can be used to assist in the restoration of artwork. Finally, the history of a piece of artwork to its final form can be
revealed. This applies particularly to paintings. For example, underdrawings¹, retouchings, and pentimenti² can be revealed. In the late 1970’s, long before the VASARI project came about, the National Gallery used a spectrophotometer to track the changes in artwork (Wright, 1981). This was much more time consuming, however, since each section of the artwork, as well as each wavelength within the visible spectrum, had to be measured separately.

In terms of lighting, several things must be considered. The lighting must be bright enough that the exposure time is relatively short. In addition, the types of lights must be considered. This is especially important for artwork where certain lights could result in damage to the piece. It is important that the subject be brought in as close to the time that it will be digitized as possible. Many types of art are especially fragile to bright lights and/or heat typical of studio lighting. In addition, conservation of the piece often specifies that there be negligible or non-existent ultraviolet or infrared radiation, which can damage fragile pieces. For example, mercury metal iodine lamps are used only very carefully when it comes to photographing artwork. These lamps are usually referred to as HMI lamps, where H stands for Hg, mercury’s elemental symbol. They are very bright and have some UV and IR emissions (Myers, 2000). Therefore, if HMI lamps are used, a UV or IR blocking filter should be used. These types of filters should also be used with many other types of lamps. In addition, studio lamps can cause reflections on paintings, especially if they are varnished. The MARC project (Methodology for Art Reproduction in Colour), at the National Gallery of London, used polarizers to reduce the reflections on the paintings. However, this caused dark areas to appear richer and darker than they would appear in the gallery. They were also photographed without the non-reflective glass under which they are

¹ underdrawings: drawings usually done with pencil on a canvas before the paint was actually applied to a painting
² pentimenti: changes in the painting from the time the artist began it to its final form
normally displayed in the gallery, which made the paintings appear richer and more blue-green in hue when photographed (Burmeister, 1996).

Short exposure times are important to minimize noise in the resulting image. The greatest effect of noise in an image is usually in the blue region. This is because CCD detectors have the lowest sensitivity in the blue region of the spectrum (Berns, 2000, 2001; Vora, 1998). In addition, exposure times cannot be longer than necessary to produce the ideal image otherwise blooming\(^3\) will occur from saturation of the CCD array (Berns, 2000, 2001). The opposite problem occurs when the exposure time is too short. This causes quantization\(^4\) error. The exposure should be such that the majority of the range of digital values is used. The minimum values should be close to but not equal to zero and the maximum values should not reach the maximum values available (for example, 255 for 8-bit processing). In this way, it can be guaranteed that the range was not cut off on the high end (clipping), or that too large a range of values were compressed to zero on the low end.

There are several different types of noise that may have to be considered in digital imaging. If the source of the noise is known then it will be easier to minimize. However, not all noise can be controlled. Shot noise is associated with dark current, which is a random process, both spatially and temporally (Theuwissen, 1995). Shot noise can only be decreased by reducing the dark current itself. To do this, the array must be cooled (Holst, 1998). Another type of noise relating to dark current is dark current non-uniformity noise (Eastman Kodak, 2001). Dark current non-uniformity noise results from the fact that each pixel produces a slightly different amount of dark

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\(^3\) blooming: overflow of charge from an oversaturated sensor to the next one in a CCD

\(^4\) quantize: limiting the number of possible values to a discrete set of values by some set of rules
Unlike shot noise, dark current non-uniformity noise can be eliminated by subtracting a dark current frame from each image. Reset, or kTC, noise is introduced from voltage fluctuations across the capacitor when they are charged through the resistor (Theuwissen, 1995). Thermal noise is generated through the resistor in this way, causing the kTC noise (Holst, 1998). The main way to reduce this type of noise is to measure it and compensate (electronically) for it afterwards. This can be done using a technique known as Correlated Double Sampling (CDS) (Theuwissen, 1995). If the capacitor is cooled, by cooling the array, kTC noise can be reduced somewhat. However, this technique is mainly used to reduce dark current noise. kTC noise is a type of output amplifier noise and the hardest of the three to deal with. The other two types are thermal noise and 1/f noise (Theuwissen, 1995). Thermal noise is mainly due to noise generation in the MOS (metal-oxide semiconductor) transistor channels, while 1/f noise is caused when the electrons in the inversion channel causes fluctuations in the voltage (Theuwissen, 1995). Neither of these types of noise can be eliminated. However, they can be greatly reduced with appropriate design and layout of the elements in the camera. Other types of noise include photon noise, fixed pattern noise, and quantization noise, just to name a few.

File format and storage are also a large concern when digitizing images. Since conservation is such a great concern, the hope is that once an image is digitized it may never have to be again (at least not in the near future). Therefore, the original digital image, called the digital master, must be saved so that when reproductions are needed in the future, they can come from the digital master. To achieve this, the highest resolution and bit depth possible should be captured and saved. Frey and others suggest that at least 12 bits should be stored (Frey, 1999). If at all possible, the raw data should be saved and stored uncompressed, such as in 16-bit TIFF format.
High compression schemes should not be used for digital masters because of loss of quality. If any compression scheme is used, it should be lossless. This presents the problem of storage. Images of this quality can end up being very large in file size. This will limit the media types on which such images can be stored. In addition, the media type must be stable and reliable. If there are many digital images in a collection, expense can also be a problem. More storage space means higher cost, and some storage mediums are more costly than others. Finally, there needs to be a procedure to backup and update the storage media to insure longevity of the digital information.

2.2 Image Quality

There are two main types of image quality (Dalal, 1998; Natale-Hoffman, 1999). When the quality of an image is objective, it is known as image quality metrics. However, when the image is looked at subjectively, it is known as image preference. When images are being evaluated objectively, the task usually involves measurement instruments of some type to actually assess the physical characteristics of the image. Image preference experiments, however, involve observers deciding, for example, which image they prefer.

Much of the image quality problem relates to the fact that a "high-quality" image may mean different things to different people (Nilsson, 1997). For example, an image of a given quality might be acceptable for one purpose but not for another. Therefore, one or the other of these methods is used depending on the needs of the research in question. Each has its own advantages and drawbacks. For example, image quality metrics do not result in overall image quality results. One can only measure certain aspects of the image at a time, and there is no way to know how
well the actual image will be perceived, no matter how well the image performs in this sort of experiment. On the other hand, while image preference experiments will give much information on the overall image quality and how well observers like the image, it is difficult to extract information needed for engineering improvements (Dalal, 1998). In addition, image preference experiments are very dependent on the content of the image, the experience of the observer, and as previously mentioned, the use of the image (Inagaki, 1994).

The difficulties using either image quality metrics or image preference in the evaluation of overall image quality have caused some researchers to attempt to find a connection between the two types of experiments. For example, Dalal (1998), Natale-Hoffman (1999), and their colleagues at Xerox Corporation and Fuji-Xerox Corporation have come up with “image quality attributes.” In the future, they hope to use these to be able to predict image preference using image quality metrics using these image quality attributes. Their specific focus is on hardcopy output.

To obtain a digital image, three steps are required. These are the capture, processing, and output rendering (Hubel, 1999). Each of these steps affects image quality to some degree. Since the sensitivities of most digital cameras are not linear combinations of the CIE color matching functions (the Luther-Ives condition), it is difficult to have completely accurate color reproduction. Therefore, image quality is also affected by the imperfections of the color renderings. In addition, metamerism is problematic, and becomes worse as the camera’s spectral sensitivities stray further from color matching functions.
Image quality is also affected by ISO speed of the camera (Borg, 1999). As the ISO speed increases, the noise increases. There is a similar problem in analog cameras where a larger film speed (ISO) is the result of larger film grains, and therefore a “noisier” image. In addition, blooming, quantization error, and various types of noise also affect image quality, as discussed in the previous section. Specifically, the more blooming, quantization error, and noise that can be seen in an image, the lower the image quality.

Yet another cause of poor image quality is aliasing. Aliasing occurs when high frequency patterns in an image are sub-sampled creating lower frequency patterns in the final image. Kriss (1998) states that it would be more useful to calculate a potential for aliasing in a specific system instead of calculating the actual amount of aliasing. Image sharpness, being another image quality attribute, is often dependent on aliasing. Kriss found that a small increase in sharpness creates a “seven-fold increase in the Potential for Aliasing.” If an increase in sharpness is needed to create a higher quality image, it must be determined whether the small increase in sharpness is worth the large increase in aliasing. In addition, Kriss’s research demonstrated that CCDs with color filter arrays are much more prone to aliasing artifacts than monochrome sensors.

Other factors that contribute to image quality that may be important to the current research include dynamic range, tone reproduction, and “color gamut”\(^5\) of the image, specifically as compared to the original scene (Yuasa, 1998).

\(^5\) Sensors don’t have “color gamuts.” Rather, physical properties of the imaging system affect the precision and accuracy of the image encoding.
2.3 Multispectral Imaging

Most of today's imaging technologies are based on a three-channel system. This is made possible because of the principle of metamerism (König, 1999b; Hill, 1998). Metamerism results when two colors that look the same under one light source (or to one observer) look different under another light source (or to a different observer). Any time a different system or material is used to create a reproduction, a metameric match is actually created. However, these colors will match only if the standard observer is assumed and if the original and reproductions are "referenced" to the same illuminant (Hill, 1998). For example, the colors on a CRT monitor will be metameric to the corresponding colors on a printed reproduction. This is because characteristics of the CRT phosphors are different from those of the printing inks. Even if these two images look the same in an office, they probably won't look the same to someone else under a different light source. Also, it is difficult to match every color in a reproduction to its original unless the same illuminant is used to view them (Hill, 1998).

Multispectral imaging can help or even correct many of the problems associated with three-channel systems (König, 1999b). This is especially important when exact reproductions are required, as in the replication of fine art pieces. This is true for both scientific applications of the reproductions, as well as respect for the artist's original intentions for the piece (Maitre, 1997). Multispectral imaging allows one to calculate the color of an object for any arbitrary observer and illuminant. To achieve this, information about the spectral reflectance of every pixel in a given scene must be captured (Hardeberg, 1999). Of course, this leads to a tremendously large amount of data, which must be handled efficiently in order to be useful. In addition, it is imperative that multispectral systems be compatible with current three-channel technology since
image processing software and output devices are not currently equipped to handle multispectral images (König, 1999b).

A decision has been made at the Munsell Color Science Laboratory (MCSL) that perhaps a more appropriate name for what has been called multispectral imaging in the past, would be multi-channel visible spectrum imaging, abbreviated MVSI. This abbreviation will be used in this thesis for references to any future research done at MCSL. “Multispectral” imaging or other variations will be used when referring to previous research that uses this terminology already.

MVSI is based on the idea that metamerism is eliminated when the original and the reproduction result in an exact spectral match. As the spectra of the reproduction become closer to the spectra of the original, metamerism is reduced (Berns, 1999). If an exact spectral match is achieved, changes in illumination and observer will not affect the reproduction (Berns, 1999). The original and reproductions are no longer metameric at this point. Instead they are the same color completely. In other words, they become isomers instead of metamers.

While MVSI removes the need for standardized lighting, color appearance models, and color gamut mapping, there may be a significant increase in the cost of the system (Berns, 1999).

Much of the research in the area of multispectral imaging began less than ten years ago, with most of the work performed only in the last four to five years. It has been applied to remote sensing and astronomy, as well as in the field of medical research (Swain, 1978; Abousleman, 1995; Memon, 1994; Curran 1985; Rosselet, 1995; Farkas, 1996; Yamaguchi, 1997; Ohya,
Only in the past few years has it been applied to pictorial imaging and the imaging of artwork. The application of multispectral imaging during this time has been mainly limited to subjects that do not require that all data be acquired simultaneously, such as artwork and documents. Therefore, it is possible to acquire the image data consecutively through the use of optical filters (Burns, 1996). This technique has been applied several times with variations on the procedure and subject matter. A summary of previous techniques will be discussed further on.

Much of the research that has been done relates to finding the minimum number of spectral filters and/or the minimum number of eigenvectors needed to produce the best spectral match possible, while still being practical. For the most part, the greater the number of filters or eigenvectors used in the analysis, the better the spectral estimation. The problems that must be considered include colorimetric accuracy, spectral accuracy, and noise propagation (Berns, 1999). In addition, if filters are optimized, the cost of physically producing them must be considered (Hardeberg, 1999).

Eigenvector analysis, often called principle component analysis (PCA), is a statistical method for analyzing multivariate data and is often used for the reduction of multispectral images. The technique transforms the data set into an eigenvector space, the axes of which lie along the dimensions of the greatest variance in the data set. The transformed data are called principle components. Principle components are the uncorrelated linear combinations of the original data set whose variances are as large as possible (Kachigan, 1991). In other words, the first principle component accounts for the largest amount of variance in the original data set, the second
principle component accounts for the next largest amount of variance, and so on until all variance has been exhausted. The equation for the $i^{th}$ principle component, $P_{ci}$, is shown in Equation 1.

$$ P_{ci} = e_i'X $$  \hspace{1cm} (1),

where $e$ is the $i^{th}$ eigenvector and $X$ is the original data set (Tzeng, 1999). The original data set can be approximated by a linear combination of a given number of principles components and the same number of eigenvectors. For example, if the first three principle components are required to account for a predetermined amount of variance, three eigenvectors are also needed to retain this degree of variance.

The terminology in eigenvector analysis is often confused. In the following section, the terms eigenvector and principle component will be used as consistently as possible, where appropriate, and only when consistency is accurate. For the research described later in this thesis, the terms eigenvectors and eigenvector analysis will always be used.

Cohen performed the first eigenvector analysis on reflectance spectra in 1964. He used 433 Munsell color chips and found that three principal components account for 98.18% of the variance. Using three eigenvectors, the reflectance spectra of the chips were predicted with “high accuracy” even though the Munsell color chips were created with many more than three pigments (1964).

In the late 1980’s, many researchers began experimenting with multispectral imaging and the spectral estimation of objects, which has continued up to the present time. Parkkinen, et al.
(1989) did a similar experiment to Cohen and challenged his results. Using a larger set of Munsell chips and eigenvector analysis, they determined that as many as eight eigenvectors were needed to reconstruct the spectra of the chips. Specifically, all of the spectral reflectances could be reconstructed using between four and ten eigenvectors. The reconstructions were directly compared to the original data by subtracting them. The absolute value of this reconstruction error over the wavelength region was used as a goodness metric. However, when using eight eigenvectors, enough of the spectra could be reconstructed to result in a reconstruction error of less than 0.02 units of absolute spectral reconstruction error (Parkkinen, 1989).

In the early 1990's, Dannemiller (1992) began work at the University of Wisconsin on the spectral reflectance of natural objects. He attempted to find out how many eigenvectors were necessary to accurately estimate the spectral reflectance functions of natural objects. It should be noted that natural objects usually have very smooth reflectance functions over the range of human sensitivity. This is more specifically true for inanimate objects than animate ones (Dannemiller, 1992). Using ideal observer analysis (Geisler, 1989), he determined whether an original spectrum could be distinguished from its estimated spectrum using fewer and fewer eigenvectors. As stated above, the spectral estimation will become less accurate as fewer eigenvectors are used in the analysis. The set of eigenvectors that Dannemiller used resulted from performing eigenvector analysis on the reflectance spectra of 337 natural objects. He found that by using four eigenvectors, the difference between the original and estimated reflectance spectra could hardly be detected by the ideal observer. Dannemiller realized that since real human sensitivity is much lower than the sensitivity of the ideal observer due to noise in the human visual system, that a barely detectable difference between the original and estimated
spectral data could probably be obtained using only three eigenvectors. However, this analysis was a metameric analysis and did not consider accuracy across changes in illumination.

Chiao and Cronin also decided to use natural objects for their analysis several years later (Chiao, 2000). Similarly to Dannemiller, they wanted to find the number of eigenvectors needed to estimate natural spectra. However, in their case, they wanted to image the natural environment instead of using objects taken from the natural environment. Their purpose was to use objects in an environment that a given species might actually see normally, specifically, in terrestrial or aquatic environments. In order to do this they used forest and coral reef scenes, respectively. An interference filter was used in conjunction with a CCD camera to obtain 40 images captured at 7-8 nm increments. They also analyzed the effect of natural illuminants on natural scenes. They found that the change in illumination during the day has little effect on the colors of forest scenes. Water depth, however, had a great effect on the colors underwater. Specifically, as the depth increased, the variation in the chroma of colors decreased. Overall, they found that the first three eigenvectors could reconstruct the scenes “extremely well” because they accounted for about 98% of the total variance.

The previously mentioned VASARI project began at the National Gallery of Art in the early 1990’s. The purpose of this extensive project was to detect and measure changes in the surface color of paintings over long periods of time (Saunders, 1993). Each time a painting was imaged, it would be added to an archive to be compared against previous and future images of the same painting. Although work at ENST (École Nationale Supérieure des Télécommunications, a collaborator of the VASARI project) showed that twelve filters should be the minimum number
used for spectral reconstructions (Deconinck, 1990), they chose to use only seven due to time and hardware limitations. Furthermore, their main requirement was colorimetric accuracy, not spectral estimation. Since a painting is usually too large to acquire a high-resolution image in one exposure, the VASARI project used the technique of mosaicing to reconstruct a large amount of separate images that combine to produce an image of the entire painting. In addition, another project called MARC (Methodology for Art Reproduction in Colour) evolved from VASARI (Burmeister, 1996). The MARC project successfully used colorimetric imaging to create color-accurate reproductions for print purposes. Unfortunately, an analysis of the accuracy of the end-to-end MARC system was never published.

Vrhel, Gershon, and Iwan measured 64 Munsell color chips, 120 Du Pont paint chips, and a set of 170 natural objects (Vrhel, 1994a). They used eigenvector analysis to reduce the data set, while still being able to accurately represent the full data set by estimating the reconstructions of the reflectance spectra. This information was used in later research to reproduce scanned images accurately with a small number of eigenvectors (Vrhel, 1994b). They noted that the quality of the spectral estimation is a function of the spectral sensitivity of the device used to acquire the original image and the degree of accuracy required for the application for which the estimate is used (Vrhel, 1994). For each set of samples, the overall estimation errors differed. In addition, the $\Delta E_{ab}^*$ did not necessarily decrease as eigenvectors were increased. This was because the spectral error was minimized in the reconstructions instead of $\Delta E_{ab}^*$. They concluded that to be visually acceptable, seven eigenvectors should be used to estimate the reflectance spectra for images, in general (Vrhel, 1994).
Research performed by Burns for his Ph.D. dissertation (1997) at Rochester Institute of Technology regarding image noise in multispectral imaging lead to the “Analysis of Multispectral Image Capture” by Burns and Berns (1996). Burns used a seven-channel camera to compare different techniques of spectral reconstruction. Commercially available interference filters were attached to a Kodak DCS 200m digital camera. The methods of spectral reconstruction that were analyzed in this research were spline interpolation, modified-discrete-sine-transformation (MDST) interpolation (Keusen, 1995), and a modified eigenvector analysis technique. Burns concluded that for almost all of the patches on the Macbeth ColorChecker, the eigenvector analysis technique resulted in the most accurate spectral reconstructions (1996). CIELAB values for each of the reconstruction methods were then calculated directly from the estimated spectral reflectance factors. The eigenvector analysis method also proved to be the most accurate for the colorimetric comparison.

École Nationale Supérieure des Télécommunications (ENST) in France has created a multispectral system using a Kodak Eikonix 1412 line-scan CCD camera and seven optimized filters (Schmitt, 1997; Maitre, 1997). The goal at ENST was to produce an inherently device independent imaging system using a reduced set of chromatic filters that was less expensive than previously designed systems. Eigenvector analysis and singular value decomposition were used to estimate the spectral reflectances of 1269 matte Munsell color chips. They found that a sub-optimal number of eigenvectors would result in high estimation errors for a given amount of noise in the system. As in previous research, the root-mean square (RMS) error decreased as the number of filters increased. Hardeberg, Schmitt, and Brettel later expanded on this research by using a liquid crystal tunable filter (LCTF) with a monochrome CCD camera (Schmitt, 1997;
Their multispectral system was used to simulate how the original scene would appear under different illuminants (Hardeberg, 1999). They used CIELAB as a color appearance model with the assumption that the CIELAB values of a given surface color are constant and independent of changes in the illuminant. In addition, the simulation was performed using five, seven, and ten filters to obtain the multispectral data. These two methods were compared for CIE illuminants D65, D50, A, as well as F2, and a low-pressure sodium lamp. The original "scene" included 64 oil pigments. In general, it was shown that the multispectral approach to illuminant simulation performed better than the CIELAB approach, however, results varied depending on which illuminant was simulated (Hardeberg, 1999).

Hill at Aachen University provides us with a general overview of multispectral color technology, including its problems, advantages, and how it improves upon three-channel systems (1998). He then describes the results of several reconstruction techniques used to estimate the spectral reflectances of the 354 samples measured by Vrhel, Gershon, and Iwan, described above. The reconstruction methods used were spline interpolation, modified-discrete-sine-transformation (MDST), modified-discrete-sine-transformation with aperture correction of spectral filters (MDSTA), pseudo-inverse, smoothing inverse, and Weiner inverse. These methods were used with six, ten, and sixteen filters, as well as 5 nm, 30 nm, and 50 nm bandwidths. The best results for practical applications were using the Weiner or smoothing inverse methods using ten to sixteen spectral filters and a 30 nm bandwidth (Hill, 1998, König, 1999a). Specifically, the minimum error for different bandwidths depended on the estimation method that was used.
König and Herzog also work on multispectral imaging in the same department at Aachen. They found that color difference could be greatly decreased when using multispectral image capture instead of traditional three-channel capture (König, 1999a). These results came from a simulation experiment using the previously described Vrhel data set, as well as a set of 234 random color patches printed on a Mitsubishi thermal sublimation printer. When the variability of the spectra is limited to a certain medium, the performance of both the three-channel and multispectral technologies could be improved. König (1997) also did research on reconstructing spectra using nonlinear methods. The non-linearity accounts for the fact that the intensity of the light source in an image usually changes from pixel to pixel. A fourth order polynomial was shown to work best, and the color difference was reduced by 3-5 ΔE*ab units from linear methods (König, 1997).

Yet another related publication by König, et al. (1999c) discusses how to display multispectral images on three channel display equipment. The method begins with the spectral reconstructions of the multispectral image using a 16-channel scanner for input and a smoothing inverse for the estimations. Tristimulus values are calculated for a given illuminant. Next, the relationship between the RGB color display signals and the tristimulus values is used to create an ICC device profile and a three-dimensional look-up table (LUT). It was necessary to use software without its own color management, therefore, major programs, such as Adobe Photoshop, could not be used. Since accurate rendering is the intent here, gamut mapping must be used in such a way that displayable colors should not be modified. However, non-displayable colors are modified slightly in chroma and lightness, while hue must be maintained. This was referred to as a "chroma-mapping algorithm" (König, 1999c). Their display was tested using two crayon
paintings, three watercolor paintings, one oil color painting, and one photograph. A visual comparison was performed under both tungsten and daylight illumination. The display set-up yielded excellent results for all images except for the photograph, which showed a slightly reddish shift in the reproduction (König, 1999c).

Baronti, et al., describe an application for multispectral capture in the area of imaging spectroscopy (1998). Similar to other multispectral camera systems, they used a digital camera with a set of narrow-band optical filters to capture a set of images and eigenvector analysis to reduce the data set. However, the data set in this case was a set of images, not a spectra set as in other research. Their goal was to improve upon a way to detect underdrawings and pentimenti of works of art. Eigenvector analysis was applied to 29 monochrome images (one image from each filter) and it was found that 97.72% of the variance was accounted for in the first three principal components. Baronti's conclusion was that multispectral capture and eigenvector analysis is useful in the analysis of images and for pigment identification. Around the same time, Casini, et al. (1999), also applied multispectral imaging to imaging spectroscopy. Twenty-nine filters were used in their camera, which was used to image a painting. Their study was mainly focused on the identification and distribution of certain pigments on the painting's surface (Casini, 1999). The techniques used in this study proved somewhat useful for differentiating and identifying pure pigments. However, the data was not sufficient enough for detecting underdrawings and pentimenti in the painting (Casini, 1999).

In 1999, MacDonald, et al. compared traditional eigenvector analysis for multispectral estimation on reflectance data to a Fourier analysis of the same data sets at the Color and Imaging Institute
at the University of Derby. 198 paint samples and a CMYK printed test chart from a Mitsubishi dye-sublimation printer were used as targets. Using three principal components, 97.8% of the variance in the paint sets, and 98.5% of the variance of the printed data, was accounted for. However, the eigenvectors derived from the printed samples do not fit the paint samples, showing that the estimation is target dependent. An interesting point was made in this paper about the required resolution of objects. It was stated that natural objects and scenes are not limited by the structure of the object or scene itself, but instead by the resolving power of the equipment. This is because the resolution of natural objects and scenes is almost infinite. This, however, is not true for man-made objects, which have a limited resolution (MacDonald, 1999).

Tajima, et al. (1998), has created a large database to be used for evaluating color reproduction in image input devices. It has been called ‘Standard Object Colour Spectra Database (SOCS) (Tajima, 1999). This is relevant to MVSI for the simple fact that it is yet another set of object data that can be used for research in this area. They realize that the evaluation of a system depends greatly on the samples being evaluated. The database is the largest of its type ever constructed (at the time) and includes the spectral data of 49,672 colors collected from eight categories: photographic materials, graphic printing, color computer printers, paints, flowers, leaves, human skin, and Krinov’s spectral data (Krinov, 1947) of natural objects (Tajima, 1998). However, since 30,624 of the colors are the result of graphic printing such as offset / gravure, and 7,856 of the colors result from color computer printers, a drawback of this database is that there are not actually a large amount of different colorants represented in it (Tajima, 1999). In fact, this leaves only 11,192 non-printed colors in the database. An analysis of this database
revealed that using three eigenvectors, the smallest root-mean-squared error came from the skin samples, while the largest came from the dye sublimation printer output (Tajima, 1999).

As previously stated, the evaluation of a system depends greatly on the samples being evaluated. At Chiba University in Japan, Tsumura, et al., proposed an improved way to select samples to assure accurate color reproduction (1999). Since the concern was oil paintings, 1000 color samples were mixed from oil paints and measured. The Weiner estimation method was used as their "conventional" method for reconstruction of reflectance spectra. Their new "limited samples" method was also used for reconstruction. The samples were limited based on angle and distance criteria between the first estimated spectral reflectance and the sample vectors used with the Weiner estimation method (Tsumura, 1999). They decided that 100 samples were appropriate for their limited set. Their "limited set" method greatly improved the estimation of the samples, although some changes had to be made to improve the speed of the process.

A multispectral imaging system was also developed at Chiba University for use in the spectral estimation of artwork. A CCD camera with five filters was used and the reflectance spectra of paints were estimated using eigenvector analysis and the Weiner estimation method (Miyake, 1998). A polarizing filter was used to reduce reflections on the paint surfaces. 147 oil paint samples and 1795 patches from Japanese Industrial Standards standard color charts were used. Similar to previous research, the multispectral capture and estimation methods used by Miyake, et al., improved the reproduction of artwork compared to the originals. In addition, their method was able to replicate surface characteristics of paintings. Kondou, et al. (1999) expanded on this
research to find a better compression method for multispectral imaging. Eigenvector analysis and discrete cosine transform were proposed to eliminate inter-pixel redundancy (Kondou, 1999).

Tominaga (1999a,b) described another multispectral camera using six filters and also considered using a LCTF. Two models were used in the spectral reflectance estimation. The dichromatic reflection model was used to describe the reflection of light from an object and the linear finite-dimensional model was used to describe the unknown spectral functions of the illuminant and the surface spectral reflectance (Tominaga, 1999a,b). Four colors in an image were estimated well using the proposed method.

Murakami, et al. (2001), performed another related research project in Japan. They attempted to estimate the spectral reflectances of an image using the chromatic patches on a Macbeth ColorChecker (Murakami, 2001). It was stressed, as in previous research, that the color chart that is used should be selected with careful consideration of the actual object being estimated. They used 170 natural objects as their subject and three, six, and nine filters in equal intervals over the visible range in their simulation. The Macbeth ColorChecker has relatively smooth spectral reflectances, as natural objects do. After using the Weiner estimation method, it was shown that the color of natural objects could be sufficiently reproduced using the color chart if enough filters were used. Acceptable color difference values were found using six or nine filters (Murakami, 2001).
2.4 Research at the Munsell Color Science Laboratory

There has been ongoing research in the past decade at the Munsell Color Science Laboratory (MCSL) at RIT relating to MVSI. This section will review just the highlights of research that relates to the current research. Other information can be found from Burns, 1996-1997; Imai, 1999-2002; Matsushiro, 2001; Rosen, 1999; Taplin, 2001.

The assembly of a spectral image database began in 1999 (Rosen, 1999). It was titled Lippmann2000 after the first researcher of spectral reconstruction techniques (Niewenglovsky, 1895). A goal of this project was to collect spectral images of various scenes by different techniques, specifically, of the human face. The criteria for the capture of a human face included that it needed to be fast, spectrophotometric (instead of densitometric), with easily obtainable and minimally moving parts. The database and more information can be found at http://www.cis.rit.edu/mcsl/online/lippmann2000.shtml.

The same year, Imai presented a new way to capture multispectral images using a conventional trichromatic imaging system, with only a small set of absorption filters or multi-illumination added to the setup (Imai, 1999). While this avoids the problems using interference filters, it is also a relatively low cost solution to multispectral capture. An IBM PRO/3000 digital camera system with an RGB filter wheel and a Kodak DCS560 digital camera with built-in RGB array sensors were used in the experiments. The Macbeth ColorChecker and two painted targets were used. The multi-filter approach utilized the trichromatic signals without filtering, with a light-blue filter, and with a very-light-green filter in front of the camera lens. Three techniques were used in the spectral estimations: eigenvector analysis in reflectance space, using simulated digital
counts, and using measured digital counts. Both imaging systems worked well, however, slightly better results were obtained using the Kodak camera, probably due to its increased sensitivity to light. Eigenvector analysis was found to be very dependent on the target used and it was suggested that iterative methods might improve the performance. The results from the multi-filter versus multi-illuminant approach were similar and worked as well as traditional approaches to multispectral capture.

A portion of this work was described in more detail two years later when Imai wrote a set of technical reports at MCSL that expanded on the use of the IBM PRO/3000 digital camera system and Kodak Wratten filters for multispectral capture (2001b-d). One of the main goals of the research was to eliminate the need to scan across the painting, as was done in the past. Six channels were used to obtain multispectral data. Red, green, and blue filters were used for the first three channels, and the other three channels were obtained by adding a light blue filter to the first three filters. Later on, nine channels were obtained by adding a light green-blue filter to the red, green, and blue filters. The Macbeth ColorChecker was used as a subject. It was decided that eigenvector analysis should be used as the estimation method for this research based on past research within the laboratory that suggested it was the most accurate technique (Burns, 1997). The reconstructions using six channels resulted in an average RMS error of 0.2 and mean ΔE*ab of 6.9. Using nine channels, the average spectral mean error was 0.029, average RMS error was 0.049, and mean ΔE*ab of 2.2. These results agree with previous research that more filters (channels) will result in better estimations. Other analyses using this imaging system used sets of 147 and 105 painted patches, along with the ColorChecker. Specific reconstruction methods were also tested in this research. It was found that reconstructions resulting from eigenvector
analysis done in a proposed empirical space, a "pseudo-K/S" space, were better than those performed in reflectance or Kubelka-Munk (K/S) spaces. Only six eigenvectors were required for good spectral estimations in the new empirical space, whereas nine and twelve were necessary for the reflectance and K/S spaces, respectively (Imai, 2001b-d).

Other work at MCSL includes a characterization of the Quantix 63-3E monochrome CCD camera by Shin (2001). Shin found the linearity, noise, gain, and dark current noise of the Quantix, as well as its spectral sensitivity. He also found that a VariSpec LCTF could be used with the Quantix camera for added control. Imai and the author conducted similar experiments to obtain better accuracy earlier this year. The results of these experiments are discussed in appendix 10.2.

The Quantix camera was recently used in experiments to find an optimal filter set for colorimetric and spectral accuracy (Imai, 2001a; Quan, 2001, Quan, 2002). Quan (2001, 2002) optimized three filters from a set of 40 Schott glass filters to obtain good colorimetric performance. Vora and Trussell’s $\mu$-factor and the proposed Unified Measure of Goodness (UMG) were used to select the best filters. About 10 times as much computation is needed for the UMG; however, it is a good complement to $\mu$-factor for analyzing the results of this research because it takes into account real-world characteristics in the system, whereas $\mu$-factor assumes a noiseless world (Quan, 2001). Imai (2001) expanded on this research by using Quan’s three optimized filters and chose two more to add to the set in order to create a multispectral system. The fourth filter was chosen to be a near infrared band-pass filter. An optimization process was used to select the fifth filter by minimizing a color difference equation, metamerism index, and
the root-mean-square error factor between the measured and reflected spectral reflectance. The results were mean $\Delta E^*_{94}=0.8$, maximum $\Delta E^*_{94}=5.3$, and the average spectral root-mean-square error factor was 0.03 for the five filter system (Imai, 2001).

Matsushiro, et al. (2001), proposed a new data compression method for multispectral imaging using eigenvector analysis and the color matching functions. Their visually lossless compression method attempts to reduce redundant data by resampling the spectral values based on the independence of the color matching function vectors. They used two sets of data for their experiment, 105 reflectances created by MCSL and 170 reflectances from North Carolina State University. With this compression method, 16.6% to 33.2% of the data can be reduced with no visual loss compared to the traditional eigenvector analysis method of data compression.

For more information on research at the Munsell Color Science Laboratory regarding multi-channel visible spectrum imaging, or any other topic, please see http://www.cis.rit.edu/research/mcsl/research/reports.shtml.

2.5 Display Characterization

In 1998, Fairchild and Wyble characterized an Apple Studio Flat Panel liquid crystal display (LCD). Their goal was to use the results to decide if the display was suitable for the presentation of stimuli in psychophysical experiments, as well as to find out if CRT characterization techniques can also be used for LCDs. It took about 45 minutes of warm-up for this display to reach a stable level. The spatial dependence of this display was found to be negligible. In other words, a color displayed on one portion of the monitor will have very little effect on the color on
another portion of the monitor. The primary chromaticities of this display were found to be very constant after a black correction. In addition, the additivity of the display was preserved along all dimensions, including luminance. The luminances for the red, green, and blue channels were summed and compared to the luminance for the white to check the additivity. Another important finding was that the GOG (gain-offset-gamma) model (Berns, 1996; 1997) that works well to describe the opto-electric transfer function characteristic of computer CRT displays, does not work well to describe liquid crystal displays. Instead a LUT (look-up table) was used and performed adequately.

Gibson and Fairchild (2000) performed similar experiments on an SGI 1600SW and an IBM prototype display. Both of these are LCD flat panels. The results were compared to those of a Sony GDM-F500 flat-screen CRT display. The spectral variability was found to be quite stable for all displays. The spatial independence and chromatic constancy were both found to be quite good for all displays. Unlike the Sony CRT and the SGI LCD displays, however, the IBM LCD was found to have very poor additivity characteristics. The GOG model worked well for both the Sony, as expected, and the SGI LCD. However, the LUT model improved the results of the SGI somewhat. However, none of the models used to describe the IBM performed well.

As part of his 2002 master’s thesis, Calabria characterized an Apple Cinema LCD. The results of his analysis were comparable or better than those of Gibson and Fairchild (2000) and Wyble and Fairchild (1998). The same LCD was also used in this thesis. The characterization performed by the author, with further comparisons to the work discussed in this section can be seen in Appendix 10.1.
3 OVERVIEW

The main objective of this research is to determine which of the MVSI techniques applied at MCSL will produce the most accurate reproduction of an original target. The result will be determined based on both color reproduction accuracy and spatial image quality. The images will be assessed during a paired-comparison psychophysical experiment, which will be discussed in Chapter 6.

First, Chapter 4 will detail all aspects of the imaging process, including the targets used. The procedure used to acquire the images used in the experiment will be outlined. Next, transformations from digital counts to reflectance were derived and applied to the images. This will be discussed only briefly in Chapter 5, since it was not a direct part of the author's research and is beyond the scope of this thesis. The interested reader can consult a technical report by Imai, Taplin, and Day (2002). This chapter will also outline the image manipulations necessary to prepare them for the experiment. Chapter 6, which discusses the psychophysical experiment, will include a description of the user interface, the set up of the experiment, descriptions of all experiments, and all analyses.
4.1 The Cameras

Two cameras were used for imaging in this research. First, all MVSI work was performed with a Roper Scientific Photometrics Quantix monochrome camera. The characterization of this camera is discussed in Appendix 10.2. This camera has a grade 3, model KAF6303, CCD that is cooled by forced-air (Roper Scientific, 2000). A Unaxis/Balzers broadband near-infrared radiation reduction (cut-off) filter (UBO 110-RE) was used in all of the Quantix imaging. Figure 1 shows a picture of this camera with a liquid crystal tunable filter and a lens attached to it. The technique for producing multiple channels with this camera is described in Chapter 4.2.

![Roper Scientific Photometrics Quantix Camera with the LCTF.](image)

The Nikon Professional D1, a typical professional-grade single lens reflex digital camera, was used for verification that the MVSI system in this research performs better, in terms of color
accuracy, than a good quality consumer camera. The D1 has a 2.75 mega-pixel CCD with a resolution of 2012 x 1324. This camera is shown in Figure 2.

![Nikon D1 camera](image)

Figure 2. Nikon D1 camera (Nikon, 2002).

Both the Quantix and the Nikon D1 cameras were fitted with a Nikon Nikkor 105 mm lens set to f/11 for all imaging. The Quantix settings were identical to those used in its characterization, described in Appendices 10.2. A speed of 5 MHz and a nominal gain of 2 were used. These were set using the software described later in Chapter 4.5.

### 4.2 Creating Multiple Channels

The MVSI images used in the psychophysical experiment were taken during two different sessions. In the first session the narrow band imaging, using a liquid crystal tunable filter (LCTF), was performed, creating thirty-one channels. A Cambridge Research and Instrumentation, Inc. (CRI) LCTF with a Varispec controller was used to create the thirty-one channels used in the narrow band imaging. Similar results could have been produced using a set of interference filters; however, because of their angle of incidence dependence it was decided
that the LCTF would be used (Imai, 2002). In addition, using the liquid crystal tunable filter would create better image registration since there are no moving parts in the system. The LCTF has two settings: high-contrast narrow band and a medium-contrast broad band bandwidth. The broad band setting was used in order to allow more light into the system. It should be noted, however, that this “broad band” setting results in much narrower channels than our actual wide band imaging system, which uses filters. Thus, in this research, this is called the narrow band imaging system. The thirty-one channels created using the LCTF are shown in Figure 3. The bandwidth at half-height varied from 20 to 60 nm approximately.

![Figure 3. Spectral transmittance of LCTF at 31 wavelengths from 400 nm to 700 nm.](image)

The wide band imaging was performed in the second session. First, six filters were used, creating six channels. These were denoted, for the purposes of this research, near infrared, red, yellow,
green, turquoise, and blue. The red, green, and blue filters were previously chosen during extensive research on the design of optimal spectral sensitivities for a digital imaging system (Quan, 2001, 2002). The filters were optimized for various illuminants and were evaluated with several metrics. Second, three of the first six filters were used (red, green, and blue), along with an extra filter (Kodak Wratten No. 38), creating a second set of six channels. Previous research in the laboratory established that using this filter, in conjunction with red, green, and blue filters, produces improved results. This research was described in Chapter 2.4.

Six glass filters were used for the wide band imaging. These were glued combinations of Schott glass filters. They were held in an Interactive Scientific Imaging Systems (ISI) filter wheel. The filter wheel held up to six, four-millimeter thick, glass filters. The optimization of the six filters was described in more detail in Chapter 2.4. The spectral transmittances of the filters are shown in Figure 4. A picture of the filter wheel, along with the filters that were used in place, is shown in Figure 5.
Both the narrow band and wide band images were taken with the Quantix camera. Another set of images was also taken with the Quantix camera. These were three-channel images, using only the optimized red, green, and blue filters. The purpose was to have a comparison of images with greater than three channels to images that use only the typical three channels, while still using
the camera setup in this research. This filter set was designed to perform as a colorimeter when used in conjunction with a well designed imaging system (Quan, 2001, 2002).

The seventh filter, which was used in conjunction with the red, green, and blue filters from the initial six filter set, was a Kodak Wratten No.38 and is visually light blue in color. Its spectral transmittance is shown in Figure 6. This is a gelatin filter colored with organic dye to achieve its unique spectral characteristics (Edmund Optics, 2002).

![Figure 6. Spectral transmittance of the Kodak Wratten No.38 filter.](image)

A Kodak absorption filter (neutral density filter 0.5) was also used in all of the wide-band imaging. This filter assures that the exposure is no less than 100 ms for every channel. This is
important because of the uncertainty of the Quantix’s mechanical shutter at shorter exposure times.

4.3 Targets

For this research, in particular, the spectral image capture method that is ultimately chosen should be target independent to the highest possible extent. This is important so that a variety of media, colors, and textures can be well-reproduced with the method. Objects used for imaging were chosen based on their ability to show the variation in the quality of the different capture methods. Targets were chosen based on criteria that were deemed important given that this work is being done for the benefit of accurate reproductions of artwork for museums.

An important requirement for the objects chosen for imaging in this research is that they put the necessary strains on the system in order to exploit its weaknesses. For example, in scenes with gradations, flat color surfaces, or different spatial attributes, noise might be more or less apparent than under other conditions. The objects chosen were intended to show these flaws, so that it might be improved and corrected to the best possible degree.

Several targets were used in this research. The first target, designated cc, included a Gretag Macbeth ColorChecker and an original watercolor painting by Ross Merrill of the National Gallery of Art, Washington, D.C. The second target, ccdc, included a Gretag Macbeth ColorChecker DC and set of Gamblin Conservation paint patches. These patches consist of many important pigments on an artist’s palette. The third target, paint, consisted of large paint chip samples by Sherwin Williams.
The next three targets were three-dimensional object set-ups. Three-dimensional objects are necessary in order to show defects in the system relating to shading, gradients, saturation, etc. Most of these effects are related to the illumination of a three-dimensional surface, in general. However, such objects were used to show that the system could be employed in every day scenes, and not just two-dimensional images.

The first three-dimensional object set-up, designated *fruit*, included a fruit and vegetable scene and a miniature Gretag Macbeth ColorChecker. This target included very chromatic colors, many of which were out of, or very close to, the gamut of the display device. It also consisted of some higher frequency patterns in the cloth and basket used. The next target, *nature*, included a nature scene with birds and insects on a nest, as well as a set of paint chips by American Heritage. The nest had high frequency patterns, and the birds and insects were very chromatic. The third set-up, *baby*, included baby toys on a baby blanket. This target contained some high and low frequency patterns, as well as chromatic primary colors.

All six of these targets included a Halon tablet made up of 20 grams of Polytetrafluoroethylene Resin (PTFE), usually referred to as Halon, pressed to one metric ton. Two final targets were also imaged. These were used for spatial corrections and consisted of gray Color-aid paper, specifically, GRAY 4 and GRAY 6.5. Table I describes the targets, as well as the abbreviations used for them. Figure 7 shows the targets.
Table I. Targets imaged in this research.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cc</td>
<td>ColorChecker and Merrill watercolor</td>
</tr>
<tr>
<td>ccdc</td>
<td>ColorChecker DC and Gamblin Conservation paints</td>
</tr>
<tr>
<td>paint</td>
<td>Sherwin Williams large paint chips</td>
</tr>
<tr>
<td>fruit</td>
<td>Fruit and vegetable scene with mini ColorChecker</td>
</tr>
<tr>
<td>nature</td>
<td>Nature scene with American Heritage paint chips</td>
</tr>
<tr>
<td>baby</td>
<td>Baby toys and blanket</td>
</tr>
<tr>
<td>ltgray</td>
<td>Color-aid paper GRAY 6.5</td>
</tr>
<tr>
<td>dkgray</td>
<td>Color-aid paper GRAY 4</td>
</tr>
</tbody>
</table>
4.4 Set Up

All imaging was performed in the Spectral Color Imaging Laboratory at the Center for Imaging Science at RIT. This laboratory is painted black to reduce unwanted flare and reflections. The section of the laboratory used in this research is described below. The experimental set-up is graphically depicted in Figure 8. A photograph of the set-up is shown in Figure 9.
Figure 8. Experimental set-up for imaging with Quantix camera.

Figure 9. Photograph of experimental set-up for imaging with Quantix camera.
An easel is against the back wall and was used to hold all targets upright and perpendicular to the floor. Directly across from the easel was the camera (either the Nikon or Quantix) on an Industria Fototechnica Firenze Minisolon 190 monopod with a Bogen Manfrotto 3029 head. The ElinChrom ScanLite Digital 1000 studio lamps were set up facing the easel so that the light hit the targets at approximately forty-five degrees on either side. Between the camera and the rest of the set-up was a baffle of black paper. The roll of black paper was held on a typical studio backdrop holder and had a square of about 8.5 inches by 6.5 inches cut out of it for the lens. Behind the camera, there is a table that holds all controlling equipment. This includes a PC computer running Windows 2000 with a Sony LCD monitor. In addition, the Cambridge Research & Instrumentation (CRI) Varispec controller for the liquid crystal tunable filter (LCTF) is here.

4.5 Software

There were two main pieces of software that aided in the imaging process. First, Digital Optics V++ software, version 4.0, directly controlled the Quantix camera. V++ is a software tool with a graphical user interface (GUI) that easily performs advanced imaging in connection with Roper Scientific cameras, including the Quantix. This software was controlled by a combination of VPascal and MathWorks MATLAB, version 6.0. All custom code used in the imaging process was written by Lawrence Taplin and Francisco Imai.

4.6 Imaging

Each of the six targets (plus the two gray paper targets) was imaged using the narrow band and all wide band techniques. In addition, they were also imaged using the Nikon D1 camera. The
maximum digital count in a 12-bit imaging system is 4096. A value of 3800 digital counts was hypothesized to be optimal for a “pure” white in the scene in order to remove the chance of oversaturation. A MATLAB program (find_times.m) manipulated the exposure time until a value between 3750 and 3850 digital counts was found for the halon tablet found on each target. Tables II and III show the exposure times for the wide band and narrow band imaging, respectively. Figure 10 shows a plot of exposure time versus wavelength for the narrow band imaging. For each exposure time, a dark current image was also taken, with the camera shutter closed. These images were subtracted from the rest of the images, as described later in Chapter 5.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Time (ms)</th>
<th>Time with Wratten No. 38 Filter (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near IR</td>
<td>118</td>
<td>1850</td>
</tr>
<tr>
<td>Red</td>
<td>686</td>
<td>4500</td>
</tr>
<tr>
<td>Yellow</td>
<td>663</td>
<td>2150</td>
</tr>
<tr>
<td>Green</td>
<td>900</td>
<td>2050</td>
</tr>
<tr>
<td>Turquoise</td>
<td>812</td>
<td>1690</td>
</tr>
<tr>
<td>Blue</td>
<td>2378</td>
<td>3500</td>
</tr>
</tbody>
</table>

Table II. Exposure times for wide band imaging.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Time (ms)</th>
<th>Wavelength (nm)</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>51424</td>
<td>560</td>
<td>673</td>
</tr>
<tr>
<td>410</td>
<td>76849</td>
<td>570</td>
<td>577</td>
</tr>
<tr>
<td>420</td>
<td>47603</td>
<td>580</td>
<td>505</td>
</tr>
<tr>
<td>430</td>
<td>30972</td>
<td>590</td>
<td>382</td>
</tr>
<tr>
<td>440</td>
<td>20622</td>
<td>600</td>
<td>340</td>
</tr>
<tr>
<td>450</td>
<td>13793</td>
<td>610</td>
<td>265</td>
</tr>
<tr>
<td>460</td>
<td>9529</td>
<td>620</td>
<td>236</td>
</tr>
<tr>
<td>470</td>
<td>7076</td>
<td>630</td>
<td>212</td>
</tr>
<tr>
<td>480</td>
<td>4367</td>
<td>640</td>
<td>191</td>
</tr>
<tr>
<td>490</td>
<td>3447</td>
<td>650</td>
<td>173</td>
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<tr>
<td>500</td>
<td>2741</td>
<td>660</td>
<td>158</td>
</tr>
<tr>
<td>510</td>
<td>2166</td>
<td>670</td>
<td>146</td>
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<tr>
<td>520</td>
<td>1477</td>
<td>680</td>
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<td>530</td>
<td>1191</td>
<td>690</td>
<td>129</td>
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<td>540</td>
<td>962</td>
<td>700</td>
<td>135</td>
</tr>
<tr>
<td>550</td>
<td>797</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table III. Exposure times for narrow band imaging.
Figure 10. Exposure times versus centered wavelength for LCTF.

Figure 10 has two interesting features. One is that the exposure times at short wavelengths are much longer than those at long wavelengths. This is because the transmittance of the LCTF at shorter wavelengths is much lower than at longer wavelengths. In addition, the light source has lower radiance at shorter wavelengths, and the CCD sensor has lower quantum efficiency at shorter wavelengths. The second feature is that the exposure time at 400 nanometers is shorter than at 410 nm. Figure 11 shows the spectral transmittance of the LCTF set to 400 nm (this figure has a smaller scale than that of figure 3). Note that there are leaks in the red region of the spectrum. These leaks are due to the LCTF being built using a polarizing filter.
4.7 Saving Images

All Quantix images were saved as 12-bit TIFF images in the camera’s V++ software. The images taken with the Nikon D1 camera were saved as uncompressed raw images. They were then resaved in 16-bit TIFF format in the Nikon Capture Software.
Various combinations of image capture and image reconstruction techniques were used for the psychophysical experiment. Several pre-processing steps were involved in preparing the images for the experiment. First, the digital counts of the dark current images were subtracted from the digital counts of the main images to remove the dark current noise, or dark current non-uniformity noise, from the images. Next, since the images obtained with the Quantix camera were taken as separate channels, they had to be registered. This was done via a combination of software, including ENVI, The Environment for Visualizing Images, by Research Systems, Inc., and MATLAB. ENVI was used to figure out the necessary warping needed to register the images as accurately as possible. MATLAB was then used to implement the required translations, rotations, and warping. Note that no registration manipulations were necessary for the images taken with the liquid crystal tunable filter because there are no moving parts in the LCTF, and therefore, misregistration of these images is negligible.

It is important to note that it was necessary to correct the images to take into account the non-uniformity of the illumination. The digital counts of the dark gray Color-aid paper (GRAY 4) images were used to correct the images. The general equation showing this procedure and the dark current noise subtraction is shown in Equation 2.

\[
DC_{\lambda(x,y)} = ([O_{\lambda(x,y)} - D_{\lambda(x,y)}] + [G_{\lambda(x,y)} - D_{\lambda(x,y)}]) \times \text{mean}(G)
\]

(2)

where \(DC\) is the digital counts of the spatially corrected image, \(O\) is the digital counts of the original image, \(G\) is the digital counts of the dark gray image, and \(D\) is the digital counts of the dark current image. The subscripts \(x\) and \(y\) are the image dimensions. Multiplying by the mean of the gray image scales the digital counts back to an appropriate level.
Finally, the images were transformed into colorimetric images and then final spatial processing was performed to finalize the images for the experiment. Chapters 5.1 and 5.2 describe these important steps.

5.1 Transformations

The process of the reconstruction of multispectral images requires that they be transformed from their multi-channel state (in digital counts) into spectral reflectance and then into colorimetric images (made up of CIE tristimulus values) that can be then sent through an inverse monitor model to be viewed later. This section will discuss the different types of transformations used in this research. Chapter 2.3 provides more information on this process, as well as references for the interested reader.

Knowledge of the process of transforming the images for use in the experiment is important for a full understanding of the experiment and its results. This section of the research was performed by Taplin and Imai. It will be described only briefly since it is not a major part of this author’s research.

Several transformations were used in creating the images for the psychophysical experiment. The transformations were created using the ColorChecker DC target. Three targets were used as verification targets: the Macbeth ColorChecker, the set of Gamblin paints, and the Sherwin Williams paint chips. These verification targets show the robustness of the transformations. As previously mentioned, the Gamblin target is especially important since the goal of this research is related to the accurate reproduction of artwork.
In creating these transformations from digital counts to reflectance, a pixel-by-pixel approach was used. The target was masked electronically. All of the masked pixels for each patch were used for the transformation. In other words, instead of using only one digital count value for each patch, many values were used. An average-based approach (using only one digital count) was abandoned since it neglects the variability inherent in a digital image even over a patch comprised of a single given color.

The general equation for the transformation from digital counts to reflectance is shown in Equation 3:

\[
R(\lambda, p * n) = M_{(m,m)} D C_{(m,p * n)}
\]  

(3),

where \( M \) is the \((31 \times 31)\) transformation matrix, \( R \) is the matrix of known reflectances of the original target, and \( D C \) is the matrix of the patch digital counts following the spatial correction (see Equation 2). The subscript \( m \) represents the number of channels; in this case, thirty-one channels. The number of pixels per patch and the number of patches are represented by \( p \) and \( n \), respectively.

For the narrow band images, a simple pseudo-inverse transformation was used to create the transformation matrix. Equation 4 shows this transformation:

\[
M_{(m,m)} = R(\lambda, p * n)(D C_{(m,p * n)})^T[(D C_{(m,p * n)})(D C_{(m,p * n)})^T]^{-1}
\]  

(4),

where, the superscript of \( T \) denotes a matrix transpose and the exponent of \(-1\) denotes a matrix inversion.
Due to the complexity of Equation 4 and its subscripts, an example calculation is given. There are 239 patches from the ColorChecker DC target that were used in creating the transformation matrices. For simplicity, the average-based approach will be described (although it was noted above that a pixel-based approach was actually used in this research). Therefore, the subscript \( p \) would equal one (1), in this case. The subscript \( m \) will equal 31 for the narrow band images. So, DC is a \((31 \times 239*1)\) matrix. A pseudo-inverse is applied to this \((31 \times 239)\) matrix. The \((31 \times 239)\) \( R \) matrix of known reflectance spectra is multiplied by the now (after the pseudo-inverse) \((239 \times 31)\) DC matrix. This results in the expected \((31 \times 31)\) transformation matrix, \( M \). Note that for a pixel-based approach, the matrices would be larger in the patch dimension (here, 239), but would still result in a \((31 \times 31)\) transformation matrix.

The \((31 \times 31)\) matrix used to transform digital counts to reflectance for the narrow band images is represented in Figure 12. Note that the y-axis goes from one to thirty-one and is labeled \textit{Wavelength Number}. The wavelength number represents the wavelength values from 400 to 700 nm in ten degree increments. This will be true for all matrix visualization plots.
Figure 12. Visualization of the transformation matrix from digital counts to reflectance using a pseudo-inverse for the narrow band images.

A similar transform was used for two of the transformations of the wide band images: once for the six filter images and once for the three filter images with the Wratten No.38 filter. The resulting transformations matrices are (31 x 6). Figures 13 and 14 show representations of the transformation matrices for the wide band images using a pseudo-inverse.
Figure 13. Visualization of the transformation matrix from digital counts to reflectance using a pseudo-inverse for the wide band images from six different filters.

Figure 14. Visualization of the transformation matrix from digital counts to reflectance using a pseudo-inverse for the wide band images from three filters (RGB) plus the Wratten filter.
The two sets of six channel images were also transformed using a two-step process using eigenvector analysis. First, a set of eigenvectors was derived from the reflectance of the target. After preliminary analysis was performed, it was decided that more than six eigenvectors produced only a negligible increase in the performance of the transformation (Imai, 2002). From thereafter, six eigenvectors were always used in the transformations. The second part of the process includes a pseudo-inverse calculation to calculate a transformation matrix. Equation 5 shows this calculation:

$$M_{(q,m)} = (E_{(m,q)})^T[(E_{(m,q)})^T]^{-1}R_{(\lambda,p^*n)}(DC_{(m,p^*n)})^T[(DC_{(m,p^*n)})^T]^{-1}$$

where $E$ is the matrix of eigenvectors and the subscript $q$ is the number of eigenvectors (six, in this case).

Another sample calculation is given. Again, the 239 patches from the ColorChecker DC target were used, as well as an average based approach for simplicity. So, the subscript $p$ equals one (1). The subscript $m$ will equal 31 for the narrow band images. So, $DC$ is a $(31 \times 239*1)$ matrix. Eigenvector analysis is performed on the $(31 \times 239)$ matrix of reflectances, $R$, to result in a matrix of $(31 \times q)$ eigenvectors. For our purposes, $q$ is always equalled to six (6). So, $E$ is a $(31 \times 6)$ matrix. A pseudo-inverse is applied to the $E$ and $DC$ matrices. The now (after pseudo-inverse) $(6 \times 31)$ $E$ matrix is multiplied by the $(31 \times 239)$ $R$ matrix of known reflectance spectra, which is then multiplied by the now (after the pseudo-inverse) $(239 \times 31)$ $DC$ matrix. This results in the expected $(6 \times 31)$ transformation matrix, $M$.

Figures 15 and 16 show representations of the transformation matrices for the wide band images using eigenvector analysis.
Figure 15. Visualization of the transformation matrix from digital counts to reflectance using eigenvector analysis for the wide band images from six different filters.

Figure 16. Visualization of the transformation matrix from digital counts to reflectance using eigenvector analysis for the wide band images from three filters (RGB) plus the Wratten filter.
The three-channel RGB image transformation was a simpler pseudo-inverse. First, tristimulus values were calculated from the known reflectances, using traditional equations. Next, a pseudo-inverse was applied, as in Equation 4, using tristimulus values instead of reflectances to create a transformation matrix. In other words, a $(3 \times 239)$ matrix of tristimulus values is used instead of the $(31 \times 239)$ reflectance matrix described earlier. The pseudo-inverse minimized root-mean-square error in XYZ tristimulus value space. A $(3 \times 3)$ transformation matrix is the result for each illuminant imposed when tristimulus values were calculated. The transformation matrices for the daylight and incandescent A illuminants are shown in Equations 6 and 7, respectively.

\[
R_{(\lambda,p,n)} = \begin{bmatrix}
0.01 & 0.01 & 0.00 \\
0.00 & 0.02 & 0.00 \\
0.00 & -0.01 & 0.04
\end{bmatrix}(DC_{(m,p,n)})
\] (6)

\[
R_{(\lambda,p,n)} = \begin{bmatrix}
0.02 & 0.01 & -0.00 \\
0.01 & 0.02 & -0.00 \\
-0.00 & -0.00 & 0.01
\end{bmatrix}(DC_{(m,p,n)})
\] (7)

An illuminant and observer were imposed upon the multispectral images when the transformation matrices were applied. The CIE 1931 standard observer was always used. An incandescent light source and a filtered tungsten daylight simulator were used as the illuminants. These are described in detail later in Chapter 6.1.2.

The Nikon D1 images were manipulated using a different technique. This was necessary since the consumer grade digital cameras have their own built-in gamma function. Therefore, it was essential to linearize the digital signals from the camera. A two-degree polynomial was fit
between the normalized Y (luminance) values and the normalized digital counts of the ColorChecker DC gray scale patches. Figure 17 shows this relationship. Since the polynomial fit the data well, it was not necessary to use a one-dimensional LUT or spline interpolation. Sending them back through the model linearized the digital counts. Figure 18 shows the linearized digital counts. A pseudo-inverse between the linearized digital counts and the calculated tristimulus values was used to create a matrix. Again, the pseudo-inverse minimized root-mean-square error in XYZ space.

Figure 17. Two-degree polynomial fit between the normalized digital counts of the ColorChecker DC gray scale patches and their Y values.
The tristimulus values were estimated by multiplying the digital counts of the original D1 images by the transformation matrix. These were then scaled to match the luminance of the light booth. The scale factor for each illuminant was calculated using Equation 8:

\[ scale\_factor = (\tilde{Y}^*L_B_{\text{halon}})(\tilde{Y}^*L_{\text{LCD}_{\text{white}}}) \]

where \( \tilde{Y} \) is the CIE 1931 standard observer \( \tilde{Y} \) values, \( L_B_{\text{halon}} \) is the radiance of a halon tablet under each illuminant of the light booth, and \( L_{\text{LCD}_{\text{white}}} \) is the radiance of the LCD at full digital counts (255,255,255).

### 5.2 Manipulations

The final tristimulus values resulting from the transformations were sent through an inverse monitor model to create final images. The characterization of the LCD, and the forward model created for it, are shown in Appendix 10.1. At this point, all of the images had to be rotated,
resized, and cropped in order to be finally ready for use in the psychophysical experiment. MATLAB was used to perform these functions.

The images were rotated so that they were visually parallel to the bottom of the screen. Bilinear interpolation was used for the rotations. Nearest neighbor interpolation was used for the resizing. They were cropped and resized to 512 by 768 pixels. Cropping the images was necessary, first, to be sure that all images looked the same, and second, to fit into the experimental graphical user interface. It was necessary to produce a set of resized images that showed the entire usable image for the color reproduction accuracy experiment, and a set that was cropped to the correct pixel size but that showed the image at full pixel magnification for the image quality experiment. This will be discussed further in Chapter 6.2.2.
6.1 Experimental Set Up

6.1.1 Liquid Crystal Display

The experiment was conducted on an Apple Cinema Display, which is a 22-inch flat panel liquid crystal display. It is an active-matrix LCD with 160° viewing angle. A G4 Power Macintosh computer operated the monitor. More details about the monitor and its characterization are described in Appendix 10.1. A black mask of foam core was cut to fit the LCD monitor so that the white surround of the LCD did not distract observers or give visual clues to the native white point of the display. The viewing area of the LCD was 10” x 17 ¾”.

6.1.2 Light Booth

A Macbeth Spectralight II light booth was placed to the right of the monitor. Two light sources were used as viewing illuminants in this experiment: Inc A, which is a tungsten light source, with a correlated color temperature (CCT) of 2894 K, and Daylight, which is a filtered tungsten light source meant to mimic natural daylight. This light source had a CCT of 6823 K. The normalized spectral power distributions of these light sources are shown in Figure 19.
Five aluminum screens were used under the lights in the light booth to reduce the level of illumination to approximately that of the LCD. The maximum illumination of the LCD was 111 cd/m². The back wall and floor of the light booth were covered with a black velvet fabric to emulate the mask around the LCD. This improved the visual match between the targets on screen and under the light booth by decreasing stray light on the original targets. The left hand wall of the light booth helped to shield the monitor from the illumination of the light booth. A small platform was placed in the light booth to prop up the targets for the experiment.
6.2 The User Interface

6.2.1 Matching Light Booth to LCD

It was important to match the background of the GUI to the walls of the light booth for adaptation purposes. A simple method was followed to produce this result. First, the right hand wall of the light booth was measured with a Photo-Research PR-650 spectroradiometer since this wall is in full view of the observers. The tristimulus values of the gray wall were sent through the inverse LCD model and the results were normalized by dividing by 255. The normalization was necessary because the GUI took in values from zero to one. The normalized digital counts were displayed as the background of the GUI. This was done for both light sources. The un-normalized digital counts were (144,147,187) and (228,183,138), respectively for daylight and incandescent A illuminants.

6.2.2 Final Images

There were two final sets of images. For the color reproduction accuracy experiment, the image types included the linearized Nikon D1 images, a set of six channel images using red, green, and blue filters with the Wratten No. 38 filter and eigenvector analysis for the image reconstruction, a set of six channel images using six different filters with PCA, a set of six channel images using the red, green, and blue filters with the Wratten filter and a pseudo-inverse for the reconstruction, a set of six channel images using six different filters with a pseudo-inverse, a set of thirty-one channel images (from the liquid crystal tunable filter) with a pseudo-inverse, and a set of three channel images (RGB) with a modified pseudo-inverse for the transformation. For the image quality experiment, the
same image sets were used without the D1 image type. Table IV summarizes the sets of images for the first two experiments.

<table>
<thead>
<tr>
<th>Abbrev.</th>
<th>Image Type Description</th>
<th>Color</th>
<th>IQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Nikon D1 linearized images</td>
<td>X</td>
<td>--</td>
</tr>
<tr>
<td>pca6W</td>
<td>6 channel images (RGB+Wratten) transformed using eigenvectors</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>pca6</td>
<td>6 channel images (RGBTYI) transformed using eigenvectors</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>pinv6W</td>
<td>6 channel images (RGB+Wratten) transformed using pseudo-inverse</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>pinv6</td>
<td>6 channel images (RGBTYI) transformed using pseudo-inverse</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>tf_pinv</td>
<td>31 channel images (LCTF) transformed using pseudo-inverse</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>RGB</td>
<td>3 channel images (RGB) transformed using modified pseudo-inverse</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

The first set of images, used for the color reproduction accuracy experiment, consisted of seven image types. The six targets shown in these images were displayed resized, so that the entire target could be seen, as in Figure 7. The second image set used for both the image quality and image registration experiments, consisted of six image types. These images were cropped and shown at full pixel size, showing only a section of the targets. Examples of these images are shown in Figure 20. Both of these sets of images were rendered for each of the two illuminants used in the experiment.
Figure 20. These cropped targets were shown at full pixel size for the image quality and image registration experiments.
6.2.3 GUI

The graphical user interface of this experiment was created in MATLAB. When the experiment began, a screen was displayed to collect user input. This included initials, age, sex, and expertise (expert/naïve). Figure 21 shows a screen shot.

![Figure 21. Screen shot of the initial experimental GUI, used to gather observer statistics.](image)

When the Done button was pressed, the experiment began. The experiment consisted of a total of 216 randomly selected pairs of images. The first 126 were images for the color reproduction accuracy experiment. The last 90 pairs were for the image quality experiment. The number of pairs was calculated using Equation 9:

\[ N = \left( \frac{n(n-1)}{2} \right)^T \]

(9)
where \( N \) is the number of pairs, \( n \) is the number of image types, and \( T \) is the number of targets. For example, for the seven image types used in the color reproduction accuracy experiment, there were \( [(7*(7-1))/2]*6 = 126 \) pairs.

In order to check for observer consistency, duplicate image pairs were added to the experiments. These pairs were later removed before the paired comparison and dual scaling analyses were performed. The pair that was added was the same for both the image quality and color reproduction accuracy experiments. The observer consistency was not checked for the image registration experiment since the images were the same in that experiment as for the image quality experiment, and therefore, the results would be expected to be the same. The pca6 and pinv6W pair was duplicated for every target, since this was the pair that had the most visual variation to the author. Since there were six targets used in each experiment, a total of twelve duplicate image pairs were added to the experiment, bringing the total number of image pairs up to 228.

While the images were shown randomly, they were grouped into their target subjects because of the use of comparison objects. For example, in the color reproduction accuracy experiment, all of the nature target images were randomly shown first, and then the baby targets images, etc., until all targets were shown. White noise was added between pairs to mask the preceding trial and reduce the use of iconic memory. After each set of images, a message was displayed instructing the conductor of the experiment to change the target in the light booth. The reason for this will be clear later, when the
actual experimental procedure is discussed. Figure 22 shows a screen shot of the main screen of the experiment.

![Figure 22. Screen shot of the main experimental GUI.](image)

The style of the experiment was paired-comparison. The observer was required to choose a single image before moving on to the next pair.

Two computer mice were used in the experiment. The images were chosen by clicking the button on the left-hand mouse to choose the left image and the button on the right-hand mouse to choose the right-hand image. Figure 23 shows a picture of the author simulating the performance of the experiment. In the actual experiments, the room lights were turned off.
6.2.4 Experimental Output

The output of the experiment included two text files for each observer. The first text file was a list of the observer statistics, as described above. The second text file included a list of image numbers in the order they were shown to the observer. Note that the images pairs were randomized before the experiment was conducted. The random order was different for each observer. Since the targets were shown in the same order for each observer, the images were randomized only within target type. The first column in the file denoted the left-hand image that was displayed, the second column denoted the right-hand image that was displayed, and the third column was the observer's choice (left = 1, right = 2).
6.3 Lighting and Observers

The paired-comparison psychophysical experiment was performed under two different light sources, as described in Chapter 5.1. Every other observer performed the experiment under the daylight illuminant. The rest of the observers began with the incandescent illuminant. The second time an observer performed the experiment, they did so under the other illuminant. The purpose of this was to check the robustness of the multispectral techniques under different illuminants. Except for the illumination from the light booth and the monitor, there was no extraneous light in the room.

Twenty-seven observers participated in the experiment under each illuminant. In other words, the experiment was performed a total of 54 times. There were actually 33 participating observers; however, some only participated in the experiment under only one light source or the other, not both.

The observers were a combination of faculty, staff, graduate, and undergraduate students, as well as a few observers from outside the Center of Imaging Science. They ranged in age from 22 to 48, with a mean age of 30.

Each observer was asked if they knew if they had any color deficiency, and if they were unsure, the Ishihara Test for Color Blindness was administered (Ishihara, 1962). No color deficient observers participated in the experiment. Naïve observers, those who have little experience with imaging science, were shown a preliminary "practice" experiment, to be sure they understood the
definitions used in the experimental instructions, and make sure they understood the functions of
the mice in choosing the images.

6.4 Observer Repeatability

Using the duplicate images, described in Chapter 6.2.3, the repeatability of each observer's
choices was analyzed. A MATLAB program, shown in Appendix 10.3, was used to compare the
duplicate pairs to the original pairs to see how many of the duplicate pairs, out of the twelve,
were chosen in the same way as their replicate. Observers chose an average of eight out of the
twelve repeated pairs correctly. The same consistency resulted from the experiments performed
under both light sources. The average is only slightly lower for naive observers, as a subset:
seven out of twelve were correctly chosen under daylight and six out of twelve were correctly
chosen under incandescent illumination. The small amount of non-repeatability is probably the
result of small variations in the images. This amount of inconsistency is not considered
detrimental to the analyses of these experiments.

6.5 Experiment One: Color Reproduction Accuracy

As described earlier, in Chapter 6.2.3, the color reproduction accuracy part of the experiment
consisted of the first 126 pairs of images (plus six replicates). These images were the resized
images that show the entire target, as mentioned in Chapter 5.2. For each trial pair, observers
were asked to choose which image looks most like the target in the light booth, in terms of color
reproduction accuracy. Figure 24 shows the actual instruction sheet that was given to the
observers.
MULTISPECTRAL IMAGING PSYCHOPHYSICAL EXPERIMENT

In terms of color ONLY, please choose the image that looks most like the setup in the light booth. Ignore artifacts such as sharpness, graininess, noise, and image registration. Use the left and right mice for their respective images. After several pairs, I will change the display in the light booth.

Thanks for your help!
Have some candy!!

Figure 24. Instructions used for color accuracy reproduction experiment.

6.5.1 Experiment One: Paired Comparison Analysis

Thurstone’s Law of Comparative Judgments (case V) was used to transform the observer data into interval scales (Thurstone, 1927). First, the data were transformed into a frequency matrix consisting of the tallied results for the amount of times an image type is chosen over another image type. This matrix was then converted to a proportion matrix by dividing by the number of observers. Finally, a matrix of z-scores was calculated from the proportion matrix using an inverse cumulative distribution function. The mean of
each column of z-scores is the interval preference scale. The MATLAB functions that were used can be found in Appendix 10.3.

The resultant plots of the analysis for the daylight experiment are shown in Figure 25. The image types, described previously in Table I, are shown on the x-axis. The y-axis shows the perceived color reproduction quality in interval scale units. The six plots represent the six different targets. Please note that the y-axes have different scales for each target.

The error bars on these plots were created using a simple equation for confidence intervals. They were calculated in terms of interval scale units. For a 95% confidence interval, Equation 10 was employed.

\[
Interval = R \pm \frac{1.38}{\sqrt{N}} \quad (10),
\]

where \( N \) is the number of observers and \( R \) is the interval scale that results from the paired comparison analysis. This equation was used for calculating all error bars in this research.
The plots above show that all of the image types were judged comparably to each other, with the exception of the Nikon D1 images. This is true for all targets with some variation in the degree of uncertainty. The significance of this result is that observers
judge the system used in this research as better than the traditional digital camera. All of the images taken with the Quantix camera were judged better than the Nikon D1 camera images. Figure 26 shows the results of the paired comparison analysis for all six targets averaged together. This plot distinctly shows that, regardless of the target, the D1 image type was judged as having lower image quality than the image types taken with the Quantix camera.

![Average Paired Comparison Analysis Under Daylight](image)

Figure 26. Average paired comparison results for daylight color accuracy experiment.

The plots resulting from the analysis of the experiment performed under incandescent A are shown in Figure 27.
A visual analysis of this set of plots shows that under incandescent illumination the results showed less differentiation than under daylight. The error bars that overlap to a greater degree show this ambiguity. In this case, it is not possible to conclude that any of
the image types performed better than any of the others under incandescent A illumination. Figure 28 shows the results of the paired comparison analysis under incandescent A illumination for all six targets averaged together. Again, from this plot, it is impossible to tell if any image types demonstrated higher color quality than any other image types.

![Average Paired Comparison Analysis Under Incandescent A](image)

Figure 28. Average paired comparison results for incandescent A color accuracy experiment.

### 6.5.2 Experiment One: Goodness-of-Fit Tests

There are several assumptions used in Thurstone’s Law of Comparative Judgments (case V) (Thurstone, 1927). These assumptions are that:

- all possible combinations of images have been compared,
- there is a normal distribution over time of the response to a stimulus,
- the difference between two distributions should be normal, and
- the discriminable dispersions (standard deviations) are equal for all stimuli.

Two goodness-of-fit tests were performed to evaluate the above assumptions used in Thurstone's model. The first was Mosteller's Chi-Square Test, which tells whether the data come from a normal distribution (NIST/SEMATECH, 2002). The second statistic, Average Absolute Deviation (AAD), calculates variability in the data, similar to a standard deviation statistic. However, in AAD, the distance from the mean is not squared, so the statistic is less affected by extreme observations. The MATLAB code used to calculate these statistics is shown in Appendix 10.3.6

For Mosteller's Chi-Square Test, the critical value must be much higher than the chi-value, in order to show that the data come from a normal distribution, and therefore, that Thurstone’s Law is appropriate for this data. If the AAD statistic shows less than 5% (statistic < 0.05) variability in the data, the Thurstone’s model is a good fit for the data. Table V shows the results of these statistics for the color reproduction accuracy experiment.

<table>
<thead>
<tr>
<th>Target</th>
<th>Daylight AAD</th>
<th>Daylight Chi-Value</th>
<th>Daylight Critical Value</th>
<th>Incandescent A AAD</th>
<th>Incandescent A Chi-Value</th>
<th>Incandescent A Critical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baby</td>
<td>0.25</td>
<td>297</td>
<td>25</td>
<td>0.14</td>
<td>85</td>
<td>25</td>
</tr>
<tr>
<td>CC</td>
<td>0.18</td>
<td>133</td>
<td>25</td>
<td>0.21</td>
<td>147</td>
<td>25</td>
</tr>
<tr>
<td>CCDC</td>
<td>0.20</td>
<td>190</td>
<td>25</td>
<td>0.18</td>
<td>102</td>
<td>25</td>
</tr>
<tr>
<td>Fruit</td>
<td>0.31</td>
<td>457</td>
<td>25</td>
<td>0.12</td>
<td>49</td>
<td>25</td>
</tr>
<tr>
<td>Nature</td>
<td>0.18</td>
<td>105</td>
<td>25</td>
<td>0.11</td>
<td>41</td>
<td>25</td>
</tr>
<tr>
<td>Paint</td>
<td>0.17</td>
<td>99</td>
<td>25</td>
<td>0.11</td>
<td>49</td>
<td>25</td>
</tr>
</tbody>
</table>

---

This code was written by Ethan Montag.
The table above shows that the data from the color accuracy experiment performed under both illuminants fails the goodness-of-fit tests. None of the AAD values are lower than 0.05 and the critical values are much lower than the chi-values. This shows that the paired comparison analysis performed on this data may not be valid since the assumptions of Thurstone’s Law are not met.

There are several reasons why the analysis may not be valid. First, circular triads may be present. For example, if image A is judged to be better than image B, and image B is judged to be better than image C, then image A should be judged to be better than image C. However, this may not be the case. Second, observers may have judged the images based on more than one dimension (instead of judging only color reproduction accuracy). Third, observers may have judged different parts of the image for each pair they were shown.

A dual scaling analysis was performed to further analyze the data.

6.5.3 Experiment One: Dual Scaling Analysis

Dual scaling is another technique that can be used for the analysis of categorical (as opposed to continuous) data. The purpose is to find hidden structure within a data set. It can be thought of as eigenvector analysis for this type of data (Montag, 2000). Specifically, the data are sorted into dimensions so that the first dimension holds the most amount of variance in the data, the second dimension holds less variance than the first, the third dimension holds less than the second, etc, until all dimensions have been used up. The number of dimensions, in this case, is the number of image types minus one.
Therefore, for the color reproduction accuracy experiment, where seven image types are used, there will be six dimensions. Appendix 10.3 shows the MATLAB functions used to perform the dual scaling analysis.

Figure 29 shows the results of the dual scaling analysis for the daylight illuminant. The first two dimensions are shown on the plots. The red stars represent the configurations of image types in the first two dimensions. The dotted-blue line shows the rank ordering of observer preferences from the paired comparison analysis. To interpret these plots, it is essential to note that the actual values on the axes are not as important as the relative proximity of the image types and observers on the plots. Also, as in the paired comparison plots, the scales on the dimensions of each plot are not equal. Compare these plots to those in Figure 25 to see that, for example, the observer preferences for the baby target rank pca6 as the most preferred image type and the D1 image type as the least preferred. The green circles on these plots represent the configurations of observers in the first two dimensions.
The dual scaling plots for daylight illumination show similar results to the paired comparison analysis. For example, in the plots for the baby target, all of the image types from the Quantix are close in relationship to one another, while the D1 image type is
relatively far from the others, showing that despite image content, the Quantix images were judged similarly to one another. In addition, the overlapping observer configurations show that most of the observers are relatively near to the Quantix image types and far from the D1 image type. In fact, there are no representations of observers near the D1 image type.

Unfortunately, the observers do not fall mainly in one dimension or the other. This spread of data over both dimensions shows that it may be multidimensional. Therefore, the results of the paired comparison analysis are questionable.

Figure 30 shows the variance plots that correspond to Figure 29. These plots show the variances for the individual dimensions (bars) and the cumulative variances (stars).
The plots above show that the variances in the first dimension are not much larger than those of the second dimensions. This is for the most part true for all targets under daylight. Because most of the variance is not accounted for in the first dimension, there is further evidence that the data may be multidimensional.
One fact that stands out here is that the variance plot for the fruit target shows a larger variance in the first dimension than for the other targets. This corresponds to the paired comparison plot for this target under daylight (Figure 25). The levels of uncertainty are smaller than for the other targets and the error bars are far from overlapping. In other words, a higher variance in the first dimension shows that there may be less uncertainty in the results.

Figure 31 shows the results of the dual scaling analysis for the color reproduction accuracy experiment under incandescent A illumination. The components of the plots are the same as the description for the previous dual scaling plots.
These plots are similar to those for the experiment performed under daylight illumination. The spread of the observers in the first two dimensions shows that the data may be
multidimensional. However, for the most part, they match the trends that are shown for the equivalent paired comparison plots. Unfortunately, there is a large amount of uncertainty in the paired comparison plots, along with some ambiguity in the placement of the observers with respect to the image types in the dual scaling plots. Again, this shows that under incandescent A illumination, observers may have had a harder time making definite selections in the task of choosing which image more closely matched that of the original target under the light booth.

Figure 32 shows the variance plots corresponding to the plots shown directly above.
Figure 32. Variance plots for dual scaling results for incandescent A color accuracy experiment.

The plots above show that for all targets, except for the CC target, there is very little difference between the variances for the first and second dimensions. Comparing these
plots to the corresponding paired comparison plots in Figure 27, Figure 32 shows that while there is a large amount of uncertainty in all plots, there is somewhat less uncertainty in the plot of the CC target. Again, this shows a correspondence between the first dimension variance and degree of confidence in the paired comparison results.

6.5.4 Experiment One: Qualitative Analysis of the Observer's Responses

Another interesting way to view the data is using schematic diagrams that show the observer's response patterns (Montag, 2002). In Figure 33 individual observer data is shown along the rows of the grid for the daylight illumination experiment. The columns represent the image types. A box with a lighter shade indicates that the image type in that column was chosen more frequently in the experiment than the other images types. Therefore, white boxes show often chosen image types and black boxes show rarely chosen image types. Appendix 10.3 shows the MATLAB function used to create these schematic diagrams.

---

7 The MATLAB code was written by Ethan Montag and modified by the author.
For the most part, there are few dominant patterns in these schematics. It is possible to see to some degree, however, that the D1 images have a predominantly dark stripe in their columns. The plots show a similar pattern to the paired comparison results for the color accuracy experiment performed under daylight. Specifically, the D1 images were chosen less often than the image types taken with the Quantix camera.

Figure 34 shows similar plots for the experiment performed under incandescent A illumination.
Similar to the results of the paired comparison and dual scaling analyses of the color reproduction accuracy experiment performed under incandescent A illumination, the schematics here show more ambiguous results than for the experiment performed under daylight illumination. There are almost no visible patterns in the schematic diagrams adding more evidence to the ambiguity discussed previously.

### 6.5.5 Color Difference Evaluation

The spectral reflectance of each patch on the original targets was measured and the corresponding colorimetric values were calculated. The patches included those on the ColorChecker DC from the *ccdc* target, the paint chips from the *paint* target, the Gamblin patches that are also from the *ccdc* target, and the Macbeth ColorChecker from the *cc*
target. Recall that the entire ccdc target (239 patches) was used in creating the transforms from digital counts to reflectance. The estimated colorimetric values for each patch coming out of the multispectral transforms, discussed in Chapter 5.1, were calculated for both illuminants. The actual and estimated values were compared using the CIEDE2000 color difference equation for each of the four sets of patches used and the seven different image types (CIE 142, 2001). Tables VI-VII show the results of these calculations for the daylight and incandescent A illuminants, respectively. Note that the number of patches used in the statistical calculations is also included on the table in parentheses.

| Table VI. CIEDE2000 color difference values for daylight illuminant. |
|--------------------|----|----|----|----|----|----|---|
| CCDC (239)         |    |    |    |    |    |    |   |
| **mean**           | 2.9| 1.9| 1.8| 2.1| 1.8| 1.2| 2.6|
| **maximum**        | 18.4| 4.5| 7.0| 7.8| 7.0| 6.5| 11.7|
| **standard deviation** | 2.3| 0.9| 1.0| 1.2| 1.0| 0.8| 1.5|
| PAINT (34)         |    |    |    |    |    |    |   |
| **mean**           | 3.2| 2.4| 2.3| 2.4| 2.3| 1.9| 3.1|
| **maximum**        | 7.3| 6.8| 6.3| 6.8| 6.3| 5.0| 6.7|
| **standard deviation** | 1.8| 1.7| 1.6| 1.7| 1.6| 1.0| 1.6|
| GAMBLIN (60)       |    |    |    |    |    |    |   |
| **mean**           | 3.9| 2.7| 2.3| 2.8| 2.3| 1.9| 3.2|
| **maximum**        | 18.0| 5.3| 5.5| 5.5| 5.5| 4.5| 8.9|
| **standard deviation** | 3.1| 1.2| 1.0| 1.2| 1.0| 0.8| 1.8|
| CC (24)            |    |    |    |    |    |    |   |
| **mean**           | 3.5| 2.1| 1.6| 1.9| 1.6| 1.6| 2.6|
| **maximum**        | 10.8| 7.8| 4.1| 4.4| 4.1| 7.8| 5.3|
| **standard deviation** | 2.5| 1.2| 0.7| 0.9| 0.7| 1.6| 1.3|
| **OVERALL MEAN**   | 3.4| 2.3| 2.0| 2.3| 2.0| 1.7| 2.9|

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Table VII. CIEDE2000 color difference values for incandescent A illuminant.

<table>
<thead>
<tr>
<th></th>
<th>D1</th>
<th>pca6W</th>
<th>pca6</th>
<th>pinv6W</th>
<th>pinv6</th>
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<th>RGB</th>
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<tr>
<td><strong>CCDC (239)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>2.4</td>
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<td>1.6</td>
<td>1.6</td>
<td>1.5</td>
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</tr>
<tr>
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<td>6.9</td>
<td>7.4</td>
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</tr>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>PAINT (34)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>2.2</td>
<td>2.2</td>
<td>2.1</td>
<td>2.1</td>
<td>1.8</td>
<td>2.5</td>
</tr>
<tr>
<td>maximum</td>
<td>7.4</td>
<td>6.2</td>
<td>6.6</td>
<td>6.2</td>
<td>6.5</td>
<td>4.8</td>
<td>6.8</td>
</tr>
<tr>
<td>standard deviation</td>
<td>1.3</td>
<td>1.5</td>
<td>1.6</td>
<td>1.5</td>
<td>1.6</td>
<td>1.1</td>
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<td><strong>GAMBLIN (60)</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>2.8</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>1.9</td>
<td>1.9</td>
<td>2.4</td>
</tr>
<tr>
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<td>4.1</td>
<td>4.6</td>
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</tr>
<tr>
<td>standard deviation</td>
<td>2.4</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>CC (24)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>2.8</td>
<td>1.2</td>
<td>1.6</td>
<td>1.2</td>
<td>1.4</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>maximum</td>
<td>9.0</td>
<td>4.1</td>
<td>4.8</td>
<td>3.8</td>
<td>4.6</td>
<td>9.4</td>
<td>4.6</td>
</tr>
<tr>
<td>standard deviation</td>
<td>1.9</td>
<td>0.7</td>
<td>1.0</td>
<td>0.6</td>
<td>0.9</td>
<td>1.9</td>
<td>0.9</td>
</tr>
<tr>
<td>OVERALL MEAN</td>
<td>2.6</td>
<td>1.8</td>
<td>1.9</td>
<td>1.7</td>
<td>1.7</td>
<td>1.6</td>
<td>2.1</td>
</tr>
</tbody>
</table>

The color difference evaluations show a similar trend to that of the paired comparison analysis. Overall, the results of the paired comparison color reproduction accuracy experiments showed that under daylight illumination, observers prefer all Quantix image types over the D1 image type. Under the incandescent A illuminant, all image types were preferred equally within statistical error by observers. Figure 35 shows the difference in CIEDE2000 values between the D1 image type and all other image types.
Figure 35. The difference in CIEDE2000 values between D1 image and all other image types.

Figure 35 enhances the results previously seen in the paired comparison analysis. The difference in the CIEDE2000 values from the D1 values for the daylight illumination, shown by the solid lines in the plot, are consistently higher for all sets of patches than the values for the incandescent illumination, shown by the dashed lines. The reconstruction of the images from the D1 led to lower colorimetric accuracy, especially under daylight illumination. This error, in turn, led to a decrease in the quality of the color in the reproduction. The other image types showed similar colorimetric performance, and therefore, were not differentiated in the psychophysical experiment.

Figure 36 shows plots of mean CIEDE2000 values plotted on top of their respective interval scales resulting from the paired comparison analyses for both daylight and
incandescent A illumination. Note that the plots labeled *ccdc* contain average values for the *ccdc* and *gamblin* targets, since they are on the same object set-up (see Figure 7). The left y-axis shows the interval scale for color quality, while the right y-axis shows the mean and maximum color difference values. Note that the color differences are shown in decreasing order. The color difference values are connected with a dotted-line for ease in recognizing patterns in the data.
Figure 36. Mean and maximum color difference values (black symbols) plotted on top of their respective paired comparison plots (blue symbols). On the plots, the top color difference values are the mean and bottom values are the maximum values.

Figure 36 shows, again, that the physical color differences mimic the psychophysical results. This is especially true for the maximum color difference values. While the mean color difference values give an impression of trends in the experiment’s results, the
maximum values enhance these trends. After taking a closer look at the data, it should be noted that the maximum values for the D1 and tunable filter images occur for the purplish-blue and black patches on the ColorChecker (cc) target, respectively. For the D1 image, this is not surprising since many observers noted that it was easiest to see the differences in the blue patches during the experiment.

Figure 37 shows correlation plots for these data. Interval scale versus the maximum color difference is shown for both daylight and incandescent illumination. The $r^2$ value is also shown on the plots. This value is the square of the Pearson product moment correlation coefficient, and goes from zero to one, with a value of one showing that the data are fully correlated. The $r^2$ value can be interpreted as the proportion of the variance in $y$ attributable to the variance in $x$ (Neter, 1996). Equation 11 shows the calculation of the Pearson production moment correlation coefficient ($r$):

$$ r = \frac{n(\Sigma XY) - (\Sigma X)(\Sigma Y)}{\sqrt{n\Sigma X^2 - (\Sigma X)^2} \sqrt{n\Sigma Y^2 - (\Sigma Y)^2}} $$

Equation 11

In this case, $X$ and $Y$ are the interval scale and color difference data, respectively.
Figure 37. Correlation between interval scale and maximum color difference.

The correlation plots shown above restate the previous results. The D1 image type consistently was rated low on the color reproduction accuracy scale and has consistently higher color difference values. All other image types, especially the liquid crystal tunable filter image type, were rated higher on the color reproduction accuracy scale and have
lower color difference values, for the most part. The $r^2$ values show that while the data is not perfectly correlated, there is a trend in most of the data. The average values of the *ccdc* and *gamblin* targets are highly correlated, again, mimicking the results of the psychophysical experiment.

6.6 Experiment Two: Image Quality

As described earlier in Chapter 6.2.3, the image quality part of the experiment consisted of the last 90 pairs of images (plus six replicates). These images were cropped images that showed only a small section of the target at full pixel size, as mentioned in Chapter 5.2.

The instruction sheet given to observers for this experiment was similar to that in Figure 24, for the color reproduction accuracy experiment. The actual instructions, however, read, “In terms of spatial image quality ONLY (ignore color), please choose the image that looks most like the setup in the light booth. Use the left and right mice for their respective images. After several pairs, I will change the display in the light booth.”

All analyses that were performed for the color accuracy experiment were repeated for the image quality experiment. The procedures were identical to those described above, except the D1 image type was not used in the image quality experiment. There was an expectation that the D1 image would not perform as well, in terms of color, as the images resulting from the imaging system in this research. This hypothesis had to be tested and therefore the D1 images were included in the color reproduction accuracy experiment. However, since the Nikon D1 is a lower grade camera
than our research-grade system, it was unnecessary to include these images in the image quality experiment. The same MATLAB functions were used for both experiments.

6.6.1 Experiment Two: Paired Comparison

The results of the paired comparison for the image quality experiment performed under daylight are shown in Figure 38.
The above plots show that the results of the image quality experiment are entirely target-dependent. In other words, the observers judged different image types better or worse.
depending on the particular target. For four of the six targets, however, the six-channel images that were created with the six separate filters (RGBTYI) were usually chosen to have the lowest image quality by the observers.

For the most part, the image types that were chosen to have the highest image quality came in pairs. The first pair is the two six-channel image types created with the Wratten filter (RGB+W) and the second pair is the LCTF image type and the three-channel (RGB) image type. For images captured using six-channels, it seems that capture method is more significant than the method of transformation. The only exception to this is for the fruit target. The results for the fruit target show that the images created using the LCTF were chosen by observers to have the highest image quality, while the other image types were judged equally within statistical error.

Figure 39 shows the results of the paired comparison analysis under daylight illumination for all six targets averaged together. Although the analysis shows that the results are target-dependent, a trend is obvious even when the results across targets are averaged together. As described above, the six-channel images that were created with the six separate filters (RGBTYI) were chosen to have the lowest image quality by the observers. The two six-channel image types created with the Wratten filter (RGB+W), along with the LCTF thirty-one-channel image type, had the highest values on the image quality preference scale.
Figure 39. Average paired comparison results for the daylight image quality experiment.

Figure 40 shows the results of the image quality paired comparison experiment performed under the incandescent A illuminant.
Figure 40. Paired comparison results for incandescent A image quality experiment.
Overall, the results of the image quality experiment under incandescent A are the same as for the experiment performed under daylight illumination. Namely, the results are largely target dependent.

Figure 41 shows the results of the paired comparison analysis under incandescent A illumination for all six targets averaged together. Again, while the results are target-dependent, the average results show a definite trend, very closely mimicking that of the same experiment performed under daylight illumination.

Figure 41. Average paired comparison results for incandescent A image quality experiment.
6.6.2 Experiment Two: Goodness-of-Fit Tests

Table VIII shows the results of the Mosteller’s Chi-Square and AAD test statistics for the image quality experiment.

| Target | Daylight | | | Incandescent A | | |
|--------|----------|------|------------|----------------|------|
|        |         | AAD  | Chi-Value | Critical Value | AAD  | Chi-Value | Critical Value |
| Baby   | 0.34     | 252  | 18        | 0.41           | 466  | 18        |
| CC     | 0.38     | 359  | 18        | 0.40           | 421  | 18        |
| CCDC   | 0.38     | 403  | 18        | 0.36           | 352  | 18        |
| Fruit  | 0.40     | 388  | 18        | 0.35           | 322  | 18        |
| Nature | 0.61     | 998  | 18        | 0.64           | 1263 | 18        |
| Paint  | 0.56     | 802  | 18        | 0.40           | 503  | 18        |

The table above shows that the data from the image quality experiment performed under both illuminants fails the goodness-of-fit tests. As in the previous experiment, none of the AAD values are lower than 0.05 and the critical values are much lower than the chi-values. Again, the paired comparison analysis performed on this data may not be valid since the assumed requirements of Thurstone’s Law are not met.

6.6.3 Experiment Two: Dual Scaling

Figure 42 shows the results of the dual scaling analysis for the daylight illuminant. The structure of the plots is exactly the same as the dual scaling plots in experiment one.
Figure 42. Dual scaling results for daylight image quality experiment.

Again, the dual scaling plots shown here mimic the corresponding paired comparison plots for this experiment. For example, the six channel image types that were created with six separate filters (RGBTYI), denoted pca6 and pinv6, were chosen less frequently in
the experiments, showing that observers judged these image types as having the lowest image quality when compared to the original under the light booth.

While the observer data is somewhat spread within the first two dimensions in this experiment, it falls closer to a single dimension than the data in experiment one. Therefore, while the results of the paired comparison analysis are questionable, it is still possible that the data may be unidimensional.

Figure 43 shows the variance plots that correspond to Figure 42. These plots show the variances for the individual dimensions (bars) and the cumulative variances (stars) of the dual scaling analysis for the daylight image quality experiment.
A visual analysis of the plots above show that most of the variance is in the first dimension for all targets. Therefore, the data for the image quality experiment under daylight illumination is most likely unidimensional, giving evidence that Thurstone's
Law is applicable to this data set. The interval scaling of the data from the paired comparison analysis is probably accurate.

Figure 44 shows the results of the dual scaling analysis for the image quality experiment under incandescent A illumination.
These plots are similar to those for the experiment performed under daylight illumination.

They match the trends that are shown for the equivalent paired comparison plots.
Figure 45 shows the variance plots corresponding to the plots shown directly above.

Figure 45. Variance plots for dual scaling results for incandescent A image quality experiment.
The above plots are similar to those for the daylight experiment. Again, most of the variance can be seen in the first dimension. Again, the paired comparison analysis is probably valid for these data.

6.6.4 Experiment Two: Qualitative Analysis of the Observer’s Responses

Figure 46 shows schematic diagrams that show the observer’s response patterns for the image quality experiment under daylight illumination. To review, a box with a lighter shade indicates that the image type in that column was chosen more times in the experiment.
Figure 46. Schematic plots for daylight image quality experiment.
More patterns can be seen in these schematic diagrams than in the schematics for the color reproduction accuracy experiment. They show similar results compared to the paired comparison analysis of this data. Specifically, dark vertical lines in these diagrams show that the six channel (RGBTYI) image types (pca6 and pinv6) are chosen by observers to have lower image quality. The other four image types were chosen to have higher image quality. However, the results are largely target dependent.

Figure 47 shows similar plots for the experiment performed under incandescent A illumination.
Figure 47. Schematic plots for incandescent A image quality experiment.
Again, the schematics shown here illustrate similar patterns to the schematics under daylight illumination. The patterns shown here are comparable to the results of the paired comparison analysis.

6.7 Experiment Three: Image Registration

6.7.1 Experiment Three: Description and Explanation

A suspicion arose that the results of the image quality experiment were due mainly to registration of the images. To confirm this suspicion, another experiment was conducted. It was hypothesized that if the image registration experiment correlated with the results of the image quality experiment then the suspicion would be substantiated. Image registration was evaluated using a paired comparison analysis using the 90 image pairs (with six image types) that were previously used in the image quality experiment. Only the images transformed for daylight illumination were used because the results are likely to be the same for either illumination since the same images were used for the daylight and incandescent A experiments. The same GUI and analysis was used as for experiments one and two. The MATLAB functions are shown in Appendix 10.3.

Thirteen observers participated in this experiment. Most of these observers had participated in experiments one, two, or both. The definition of image registration was described to each observer if they were not already familiar with the term. The instruction sheet given to observers for this experiment was similar to that for the color reproduction accuracy experiment, shown in Figure 24. The actual instructions, however, read, “Please choose the image with the best channel registration. Use the left and right mice for their
respective images.” The light booth was not used in this experiment since the observers were not asked to make a comparison to the original targets.

6.7.2 Experiment Three: Analysis

Figure 48 shows the results of the paired comparison analysis for this experiment.
The results of the image registration experiment are target dependant, for the most part. However, the LCTF image type is always one of the more preferred image types.
Table IX shows the results of the Mosteller’s Chi-Square and AAD test statistics for the image registration experiment.

Table IX. Goodness-of-fit statistics for image registration experiment.

<table>
<thead>
<tr>
<th>Target</th>
<th>Daylight AAD</th>
<th>Chi-Value</th>
<th>Critical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baby</td>
<td>0.38</td>
<td>153</td>
<td>18</td>
</tr>
<tr>
<td>CC</td>
<td>0.67</td>
<td>656</td>
<td>18</td>
</tr>
<tr>
<td>CCDC</td>
<td>0.45</td>
<td>264</td>
<td>18</td>
</tr>
<tr>
<td>Fruit</td>
<td>0.65</td>
<td>657</td>
<td>18</td>
</tr>
<tr>
<td>Nature</td>
<td>0.41</td>
<td>347</td>
<td>18</td>
</tr>
<tr>
<td>Paint</td>
<td>0.41</td>
<td>213</td>
<td>18</td>
</tr>
</tbody>
</table>

The table above shows that the data from the image registration experiment fails the goodness-of-fit tests. As in experiments one and two, none of the AAD values are lower than 0.05 and the critical values are much lower than the chi-values. Again, the paired comparison analysis performed on this data may not be valid since the assumptions of Thurstone’s Law are not met. However, since the goodness-of-fit tests also failed for the image quality experiment, a calculation of correlation between the two experiments may still be valid.

An $r^2$ value was calculated between the interval scales of the image quality and image registration experiments. The $r^2$ value was calculated in two ways. First, all six image types used in the experiments were used. Because the LCTF has no moving parts, the images did not need to be registered. Therefore, the LCTF image type should have the best registration of all of the image types taken with the Quantix camera. This was verified, for the most part, in the paired comparison analysis. The second way that the $r^2$ value was calculated was without the LCTF image type included. Table X shows the results of these calculations.
Table X. Correlation ($r^2$) values between image quality and image registration experiments.

<table>
<thead>
<tr>
<th>Target</th>
<th>$r^2$</th>
<th>$r^2$ w/o LCTF image type included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baby</td>
<td>0.61</td>
<td>0.87</td>
</tr>
<tr>
<td>CC</td>
<td>0.02</td>
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</tr>
<tr>
<td>CCDC</td>
<td>0.05</td>
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</tr>
<tr>
<td>Fruit</td>
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<td>0.11</td>
</tr>
<tr>
<td>Paint</td>
<td>0.35</td>
<td>0.11</td>
</tr>
</tbody>
</table>

The values in the left hand side of this table show that there is not a strong correlation between the image quality and image registration results when all six image types are included. However, when the LCTF image type is removed from the analysis, there is a strong correlation for three of the six targets. Therefore, our suspicion that the registration of the images may play a large part in the perceived image quality of the various image types is correct in some instances.

6.8 Analysis of Color Reproduction Accuracy and Image Quality Experiments Combined

The results of the previous three experiments are interesting and give some insight as to the quality of different aspects of our imaging system. However, in order to make general conclusions about the system, further analysis was performed to find the most preferred image type overall for the color reproduction accuracy and image quality experiments combined. This result informs us of the combination of the number of channels and reconstruction method for an optimal result from the imaging system.

6.8.1 Combined Paired Comparison

The paired comparison analysis was performed similarly to the analysis performed for the previous three experiments. The technique, originally described in Chapter 6.5.1, was
modified slightly so that the color reproduction accuracy and image quality experimental results could be combined for an overall analysis.

As previously described, the data were first transformed into a frequency matrix consisting of the total results for the amount of times an image type is chosen over another image type. At this stage, this was done separately for each of the two experiments. Since there were only six image types used in the image quality experiment, the frequency matrix was (6 x 6), as compared to the (7 x 7) frequency matrix for the color accuracy frequency matrix. Because the first image type (Nikon D1) of the color accuracy analysis was not used in the image quality experiment, zeros were added to the top and left of the (6 x 6) matrix so that the dimensions of both matrices were equal. The resulting frequency matrices were added for a combined frequency matrix. Next, the matrix had to be converted to a proportion matrix by dividing by the number of observers. The top row and left column of the frequency matrix was divided by half the number of observers as the rest of the matrix since the rest of the matrix accounted for both experiments at this point. Remember that both experiments had the same number of observers. Finally, the z-score matrix was calculated and converted to an interval preference scale, as previously described.

The results of the paired comparison analysis for the combined experiments performed under daylight are shown in Figure 49.
Figure 49. Paired comparison results for the combined experiments performed under daylight.

The plots above show less differentiation between imaging techniques than previous analyses. This is to be expected since the color accuracy reproduction and image quality experiments had largely different results. Therefore, when combined, there are less
extreme results. Trends from both of these experiments can be seen in these plots. For example, the plots seem to be largely target dependent, as in the image quality analysis. In addition, for the baby and fruit targets, the Nikon D1 image type was judged to have lower overall quality than the image types from the Quantix camera, as in the color reproduction accuracy experiment. In addition, less obvious trends are visible. For example, the analysis for the fruit target shows that the LCTF image type may have been judged as having higher overall quality, as in the image quality experiment analysis, but there is too much overlap in the error bars to say this for certain. This is also true for the six channel images types with the Wratten filter for several of the targets. In the image quality analysis, these two image types were chosen above all others, for the most part, and the six channel images without the Wratten filter (RGBTYI) were chosen to have lower image quality. Again, there is too much uncertainty to make this conclusion for sure when the experiments are combined.

Figure 50 shows the results of the overall paired comparison analysis for the experiment performed under the incandescent A illuminant.
Figure 50. Paired comparison results for the combined experiments performed under incandescent A.

Similarly to the previous analyses, this set of plots shows that under incandescent illumination, observers, as a whole, were more ambiguous in their judgments than under
daylight. In this case, it is not possible to conclude if any of the image types might perform better than any others under incandescent illumination. However, similar, though uncertain trends can be seen here, such as the six channel with Wratten image types being judged higher than the six channel image types (without the Wratten filter) and most were also judged higher than the D1 image type. Again, these statements cannot be stated for certain because of the large degree of uncertainty in this analysis. Again, the results seem somewhat target dependent.

Figures 51 and 52 show a different way of looking at the data in a combined capacity. The plots show average image quality versus average color reproduction accuracy for daylight and incandescent illuminations, respectively. From these plots, it is obvious that the image type resulting from imaging with the LCTF (thirty-one channels) performs the best overall. It is the only one that is very high on both the image quality and color reproduction accuracy scales under both illuminants. The six-channel image types (with the Wratten filter) also perform very well overall.

It should be noted however, that similarly to the previous paired comparison analysis plots, there is some error in these plots. The error bars would be the same length as those in previous plots. They were left out for clarity since they would have to be shown going in both the vertical and horizontal directions.
Experiments Performed Under Daylight Illumination

Figure 51. Average paired comparison results for the color reproduction accuracy experiment versus the image quality under daylight illumination.

Experiments Performed Under Incandescent A Illumination

Figure 52. Average paired comparison results for the color reproduction accuracy experiment versus the image quality under incandescent A illumination.
6.8.2 Goodness-of-Fit Tests Combined Analysis

Table XI shows the results of the Mosteller’s Chi-Square and AAD test statistics for the combined experiments.

<table>
<thead>
<tr>
<th>Target</th>
<th>Daylight</th>
<th></th>
<th></th>
<th>Incandescent A</th>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>AAD</td>
<td>Chi-Value</td>
<td>Critical Value</td>
<td>AAD</td>
<td>Chi-Value</td>
<td>Critical Value</td>
</tr>
<tr>
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<td>230</td>
<td>25</td>
<td>0.28</td>
<td>271</td>
<td>25</td>
</tr>
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<td>0.23</td>
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</tr>
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<td>503</td>
<td>25</td>
<td>0.17</td>
<td>97</td>
<td>25</td>
</tr>
<tr>
<td>Fruit</td>
<td>0.27</td>
<td>200</td>
<td>25</td>
<td>0.19</td>
<td>150</td>
<td>25</td>
</tr>
<tr>
<td>Nature</td>
<td>0.28</td>
<td>271</td>
<td>25</td>
<td>0.22</td>
<td>141</td>
<td>25</td>
</tr>
<tr>
<td>Paint</td>
<td>0.27</td>
<td>207</td>
<td>25</td>
<td>0.26</td>
<td>213</td>
<td>25</td>
</tr>
</tbody>
</table>

The table above shows that the combined data from the experiments performed under both illuminants fails the goodness-of-fit tests. As shown for previous analyses, none of the AAD values are lower than 0.05 and the critical values are much lower than the chi-values. Again, the paired comparison analysis performed on this combined data may not be valid since the assumed requirements of Thurstone’s Law are not met. However, in previous analyses, the dual scaling results always matched the paired comparison results showing that even without meeting the requirements of Thurstone’s Law, the trends shown in the analysis are probably valid. Therefore, we will assume that this is also so for the analysis for the combined experimental data.
Conclusions

Experiments were conducted under two illuminants in order to evaluate the color reproduction accuracy and image quality of several multispectral techniques using a Quantix monochrome camera as compared to that of a set of images captured using a typical professional digital camera, the Nikon D1. The multispectral capture techniques included four six-channel techniques, a three-channel technique using optimized filters, and a thirty-one channel technique. Various reconstruction transforms were used including eigenvector analysis, a typical pseudo-inverse, and a modified pseudo-inverse. Six different targets were imaged for use in the experiments.

The first experiment evaluated color reproduction accuracy. A paired comparison analysis was performed on the resulting observer data. Under daylight illumination all image types using the Quantix were preferred over the D1 image type. However, under incandescent illumination, all image types were rated equally. The three-channel image type performed as well as the image types created using more channels. The significance of this is that an imaging system with carefully designed spectral sensitivities can perform as well as multi-channel systems. There was not any target dependency in the results of this experiment.

The internal mechanisms and signal processing of the Nikon D1 camera are proprietary. However, it is known that the D1 contains a lower-grade CCD than the Quantix camera. The D1 image type yielded similar results to the other image types under incandescent illumination possibly because the imaging and reconstruction illuminants were very similar.
Two more analyses were performed on the observer data, including dual scaling and an analysis of observer’s response patterns. Both analyses showed similar results to the paired comparison analysis. All three analyses show multidimensional results. The multidimensionality may be a result of the image types all being very similar in the experiment. In other words, because observers had a difficult time choosing between images in the psychophysical experiment, they may have had to judge different sections of the image, instead of the image as a whole. This would cause some inconsistency in terms of overall color reproduction accuracy for the image types and could lead to multidimensional results.

To evaluate if physical results correlated with psychophysical results for the color accuracy experiment, trends in color difference values were compared to the results of the paired comparison analysis. The original measured data were compared with the estimated values resulting from the image transformations for images containing test targets. Overall, the results of the color difference evaluation mimic those of the paired comparison analysis. Specifically, the D1 image type, which performed most poorly in the experimental analyses, also performed poorly in the color difference analysis. This was especially true for the experiment performed under daylight illumination, and somewhat less so for the experiment performed under incandescent illumination (where the psychophysical results were more ambiguous). The D1 image type had larger maximum color differences, overall, than the other six image types. The average values, however, show that the D1 camera produced an image with relatively high color accuracy overall. Since the maximum values are significantly higher, the D1 may be useful in applications other than scientific.
The second experiment evaluated the image quality of the various image types. The results of the paired comparison analysis were largely target dependent. However, under both illuminants, for most targets, the two six channel image types created with a Wratten filter were often preferred over most other image types. The two six channel image types creating using six separate filters were often the least preferred for most image types. In addition, for the three-dimensional fruit still-life, the tunable filter image type was preferred over all other image types.

Dual scaling and an analysis of observer response patterns were also performed on the image quality data set. Both analyses show similar results to the paired comparison analysis for this experiment. The results showed that the data were probably unidimensional. After studying the dual scaling plots for this experiment, it seems that the single dimension may be related to the channels used for the image type. For most targets, the two image types created with six channels and the Wratten filter, the two image types created with six different filters, and the three and thirty-one channels image types were grouped together, respectively, in the first dimension. The identity of this dimension correlated well with the results of the paired comparison experiment. For the most part, these three sets of image types were grouped in terms of preference.

In a third experiment, the image registration experiment, it was confirmed, in at least some cases, that the image quality was based on the registration of the images. This was verified by showing that the image type created using the LCTF, which should have the best channel registration, was preferred over the other image types. (The D1 images were not included in this experiment.)
A final analysis was performed to find out what was the most preferred image type, overall. The color reproduction accuracy and image quality data was combined for this purpose. For the most part, the results of this analysis were the same as those of the color reproduction and image quality experiments combined, as expected. However, the analysis had a greater degree of uncertainty between preferences for the image types. Overall, the Nikon D1 image type was least preferred among the observers. This was expected and showed that the Quantix imaging system was superior to the typical consumer digital camera. In addition, while there was a large degree of uncertainty, it seemed that, overall, the six-channel method using the Wratten filter was most preferred, independent of the reconstruction method used. However, when the image quality and color reproduction accuracy results were compared on the same plots, it was obvious that the LCTF image type performed as well as, if not better than, the six-channel image types (with Wratten filter).

The overall result of this research is the knowledge that multispectral imaging performs well in terms of both color reproduction accuracy and image quality regardless of the number of channels used in imaging and the techniques used to reconstruct the images. However, using six channels created with the Wratten filter for imaging, together with either the eigenvector or pseudo-inverse method of reconstruction, or using the thirty-one-channel method with a pseudo-inverse, will produce the best results overall.

An extraordinary result is that the LCTF imaging performed so well, even though the larger number of channels would be expected to generate more noise in the images. Additional noise as
channels are added does not seem to be an issue. This is probably a result of the extremely low noise characteristics of this particular research camera, the Quantix.

Efforts involving the imaging of fine art would benefit from any of the multi-channel visible spectrum imaging systems discussed in this thesis. Before an imaging system is finally implemented, many factors will be considered beyond the discussion in this thesis. However, from the standpoint of this author at this point in the research process, either of the six-channel (with Wratten filter) imaging systems or the LCTF imaging system would be most advantageous. However, since registration is an extra, somewhat complicated, step in the process, using the LCTF method would probably be favorable, especially if time is a factor in the decision.
As in most research, there is room for improvement in several areas. Probably the most important of these is the seven images types used in the experiments (six in the image quality experiment). For the most part, the image types were very similar on their respective quality scales. Many observers stated that they had a difficult time making judgments during the experiments, which is probably the reason for the ambiguous preference judgments. Ideally, the image types should be different enough to make consistent judgments, but similar enough that it is not readily obvious to the observer what the answer is before the experiment takes place.

For future experiments, it might be beneficial to first perform a more extensive analysis on the targets to be imaged and included in the experiment. Specifically, an examination of what types of targets will exploit the limitations of the imaging system would be valuable. While targets in this research were chosen to do this, they were chosen purely based on speculation and theories. A more scientific evaluation of potential targets could improve the experiment greatly.

Since the results of the image quality experiment may have been related to image registration, the experiment might be improved by finding a better image registration technique for the three and six channel image types. For this research, both ENVI and MATLAB had to be used to register the images. The process was time consuming, complicated, and not very effective. In some images, registration error was obvious. Improvements in image registration are necessary in order to improve these experiments for future research.
A hard-copy experiment evaluating MVSI techniques is also recommended for future research. In this research, images were compressed for display on a three-channel monitor. By using a multi-channel printer, images would not have to be compressed as much, or at all. This will improve the quality of the images and ensure that compression techniques do not affect the results of the psychophysical experiment. For comparison, it is recommended that colorimetric images continue to be included in such an experiment.

More research in the area of multi-channel visible spectral imaging is necessary in order to further improve the color reproduction accuracy and image quality of the techniques. Techniques can be improved to become easier and more cost effective. One important improvement needed is to make the capture, analysis, and reconstruction of the large amounts of data required for MVSI more efficient.

Over the next three years, the research that began here will continue for the National Gallery of Art, Washington, D.C. and the Museum of Modern Art, New York City. The results of the experiments discussed in this thesis will, to some degree, be applied to the continuation of the research. Software with simpler user interfaces and faster run time will be developed to run the system. A better technique for accounting for uneven illumination will be developed. An important problem is the effect of inferior image registration on image quality. Better image registration techniques will be important to continue the improvement of the system. At the present time, a new camera is being evaluated for use in this research. The final goal of this research is to implement the system for research purposes within the galleries.
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10 APPENDICES

10.1 Appendix One: LCD Characterization

An Apple Cinema Liquid Crystal Display was characterized to enable the colorimetric display of the images for use in the psychophysical experiment, described in Chapter 6. The colorimetric model consisted of three one-dimensional look-up tables describing each channel’s opto-electronic transfer function and a (3x4) transformation matrix that included black-level flare. The matrix coefficients were estimated statistically by minimizing the average CIEDE2000 color difference for a dataset sampling the display’s colorimetric gamut. The LUTs were recreated dynamically throughout the optimization of the matrix coefficients. The characterization was implemented with three different instruments to check the robustness of the method.

10.1.1 Experimental

10.1.1.1 Equipment. A 22” flat panel Apple Cinema liquid crystal display powered by a G4 Power Mac was characterized. This monitor has a 160° viewing angle and an anti-glare hard coat screen treatment. More details can be found at http://www.apple.com. The gamma was set to “uncorrected gamma (native)” in the ColorSync Profile of the monitor. The white point was set to “no white point correction (native)”, and the brightness was set to the maximum setting. Three instruments were used in the characterization to check the robustness of the method. These instruments were the LMT C1210 Colormeter, which is an illuminance colorimeter, a PhotoResearch Spectrascan 650 spectroradiometer, and a Minolta CA-100 Color Analyzer. The instruments recorded the tristimulus values, the chromaticity coordinates and luminance, and the radiance, respectively.
for each instrument, of the characterization target patches. The data was translated into tristimulus values where necessary. All equipment was warmed up and calibrated as necessary. Five measurements of each patch were averaged. A white patch on this monitor with this set-up had a luminance of 111 cd/m². This was measured using a PR-650 radiometer, which was also used to measure the spectral power distribution of the monitor’s white point to be used in all colorimetric calculations. The LMT instrument was used for all preliminary experiments.

10.1.1.2 Software. The colorimetric characterization was performed through the MATLAB software environment. The code to display the test patches was written by the author. The code to interface the measurement instruments with the computer was written by Lawrence Taplin. Since MATLAB will be used as the software environment for psychophysics and colorimetric-image display, it was critical to perform the colorimetric characterization within the identical software environment. Other software may re-render the display profile.

10.1.1.3 Lighting. Measurements were taken in a completely darkened room. Any flare resulting from the monitor itself was corrected for in the model. The spectral power distribution of the white point of the monitor was used for all calculations, along with the CIE 1931 2° standard observer.

10.1.1.4 Test Image. A 400x400 pixel square patch was displayed in the center of the LCD. The remainder of the display was set to black (dr=dg=db=0) during the
colorimetric characterization and to other defined colors during the preliminary experiments.

10.1.1.5 Preliminary Experiments. Spatial dependency was evaluated with nine color patches measured with nine different backgrounds for a total of 81 measurements. Table 10-I shows the digital counts used to create the patches. The backgrounds consisted of the same colors.

Table 10-I. Digital counts of patches and backgrounds created for the spatial dependency preliminary experiment.

<table>
<thead>
<tr>
<th></th>
<th>$dr$</th>
<th>$dg$</th>
<th>$db$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Black</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Gray</strong></td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td><strong>White</strong></td>
<td>255</td>
<td>255</td>
<td>255</td>
</tr>
<tr>
<td><strong>Middle Red</strong></td>
<td>128</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Red</strong></td>
<td>255</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Middle Green</strong></td>
<td>0</td>
<td>128</td>
<td>0</td>
</tr>
<tr>
<td><strong>Green</strong></td>
<td>0</td>
<td>255</td>
<td>0</td>
</tr>
<tr>
<td><strong>Middle Blue</strong></td>
<td>0</td>
<td>0</td>
<td>128</td>
</tr>
<tr>
<td><strong>Blue</strong></td>
<td>0</td>
<td>0</td>
<td>255</td>
</tr>
</tbody>
</table>

The mean color difference from the mean (MCDM) was calculated using CIE94 and CIEDE2000. In other words, the mean CIELAB values across the nine backgrounds were calculated for each color. Then, the mean color difference for each color on the same background was calculated for each of the nine backgrounds. CIE94 was calculated for ease in comparing the results with the results of past researchers. The average MCDM was 0.10 for both CIE94 and CIEDE2000 overall, as well as across backgrounds, and across patches. This excellent result shows that a patch of pixels of a given color does not greatly
affect the main patch of pixels of another color. Therefore, the colors across the
screen are highly independent.

These results were also compared to those published by Fairchild and Wyble
(1998). Table 10-II shows the two sets of MCDMs across backgrounds and across
patches. The average result for the Fairchild and Wyble data was slightly higher,
with an MCDM of 0.20. A similar experiment by Gibson and Fairchild yielded
average MCDM values of 0.08, 0.21, and 0.68 for an SGI LCD, a Sony CRT, and
an IBM LCD display, respectively (2000).

Uniformity across the screen was also evaluated. Only the mid-section going
horizontally across the screen, where images will be displayed, was evaluated.
Three patches across the middle of the screen were measured four times. The four
measurements were for gray, red, green, and blue patches. The left and middle,
middle and right, and left and right patches were compared. Table 10-III shows
the color differences between the patches at different locations on the monitor.
The left-right comparison gave the worst results. This result seems intuitive since these are the farthest measured sections from each other on this LCD. However, all of these color differences are small. The average MCDM for these measurements is excellent at 0.18. This analysis shows that the visual evaluation of the images used in future experiments on this LCD will not be influenced by their placement on the display.

<table>
<thead>
<tr>
<th></th>
<th>Gray</th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left-Middle</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Middle-Right</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Left-Right</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.7</td>
</tr>
</tbody>
</table>

The final analysis performed was additivity. Theoretically, the tristimulus values of the red, green, and blue channels at their highest output should add to equal the tristimulus values of the pure white of the display. However, this is rarely exactly the case. Table 10-IV shows the results from this analysis, as well as the results from Fairchild and Wyble (1998) and Calabria’s (2002) additivity analyses (Calabria characterized the identical computer-controlled display). The percent error was found by dividing the measured white value by the sum of the red, green, and blue values. This display exhibited excellent additivity.

<table>
<thead>
<tr>
<th>Value</th>
<th>Measured White</th>
<th>Day</th>
<th>Fairchild</th>
<th>Calabria</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>64.91</td>
<td>1.0</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Y</td>
<td>70.36</td>
<td>1.0</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Z</td>
<td>45.23</td>
<td>1.0</td>
<td>0.2</td>
<td>1.1</td>
</tr>
</tbody>
</table>
The contrast of this display (ratio of white to black) was approximately 335:1 based on measurements using the LMT instrument. Fairchild and Wyble’s display had a contrast ratio of 250:1 (1998). Calabria, who also characterized the identical Apple Cinema Display used in this research, measured a contrast ratio of about 307:1 (2002). Obviously, the Apple Cinema Display is consistently measured to be higher in contrast than the Apple Studio Display used in Wyble/Fairchild’s research.

Since all preliminary experiments yielded good results, this LCD was well worth the time it took to characterize it for future research.

10.1.1.6 Procedure. An eleven-step ramp from 0-255 digital counts at approximately equal increments was created. This ramp data was used for red, green, and blue channels, as well as combined to create a neutral ramp. Two 5 x 5 x 5 validation data sets were created. The first set included digital count data evenly sampled from 0-255. The second set, which included digital counts evenly sampled from 0-25, was created to check that dark colors performed comparably to the rest of the color gamut. The ramp data, as well as the two 5 x 5 x 5 factorial validation data sets, were displayed on the monitor and their tristimulus values were obtained using each of the three instruments. Each recorded measurement was an average of five successive measurements. The remainder of the display was set to black.
The measured tristimulus values were normalized so that the Y value at white digital counts (255,255,255) was equal to unity. This normalization was desirable since the LMT is an illuminance colorimeter. For vision research, these tristimulus values can be converted to units of luminance by multiplying by the luminance of the display’s white point (e.g., 111 cd/m²). A lookup table for the forward model was built by piecewise cubic-spline interpolation between the digital counts and the radiometric scalars. Three one-dimensional LUTs of radiometric scalars corresponding to 256 digital counts were created for each primary ramp from the eleven-step measurements. The (3x4) transformation matrix was defined initially using direct tristimulus measurements of the black level and each channel’s maximum radiant output. Using linear optimization, the coefficients of the 3 x 4 matrix were adjusted until the average CIEDE2000 color difference between measured and estimated tristimulus values was minimized. This minimization was performed using the 11-step red, green, blue, and neutral ramp data, and both validation data sets. Therefore, the validation data were not completely independent. Figure 10-1 shows a flowchart of the entire measurement, calculation, and optimization process.
CIELAB values were calculated from both the measured and predicted tristimulus values. The Xn, Yn, and Zn values that were used in the CIELAB equations were obtained by using the reflectance of a perfect white, the spectral power distribution of the white point of the monitor, and the 1931 CIE standard observer. Color differences between the measured and estimated values were calculated using ΔE*94, as well as CIEDE2000 (CIE, 1995; Luo, 2001). This entire procedure was repeated for all three instruments.
Following an analysis to insure reasonable performance, two additional sets of measurements were taken. The first was a repetition of the first set of measurements. This set tests the display stability and model robustness. The second set was derived from the inverse model, resulting from the characterization using the LMT measurements. The measured tristimulus values were input to the inverse model and digital counts predicted. These digital counts were displayed and measured by the LMT instrument. This second set of measurements indicates end-to-end system performance.

10.1.2 Results and Discussion

Chromaticities were plotted to check if the monitor primaries were stable. Primaries are considered stable if their chromaticities do not change as digital counts change. Figures 10-2 and 10-3 show the primary’s chromaticities without and with the black-level flare correction, respectively. Correcting for flare improves the stability of the primaries for all three channels.
The initial radiometric scalars were calculated using Equation 10-1. These scalars were used to interpolate the rest of the scalars to result in all 256 scalars corresponding to the 256 digital counts in the LUTs. The three one-dimensional lookup tables are plotted in Figure 10-4.
The (3x4) transformation matrices, based on direct measurements and optimization, are shown in Eqs. 10-2 and 10-3, respectively for the LMT instrument.

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} =
\begin{bmatrix}
51.09 & 30.12 & 12.03 & 0.41 \\
27.73 & 61.51 & 11.62 & 0.43 \\
0.83 & 6.21 & 58.34 & 0.33
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]  
(10-2)
\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
51.19 & 29.96 & 11.74 & 0.40 \\
27.56 & 61.61 & 11.20 & 0.42 \\
0.53 & 5.96 & 58.48 & 0.33
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B \\
1
\end{bmatrix}
\]  
(10-3)

The color differences for the ramp/gray scale and validation data after going through the forward model are shown in Table 10-V. All color difference values are low and well within an acceptable range. For comparison, Table 10-VI shows the color differences resulting when an optimization of the 3 x 4 matrix and updated LUTs is not used. There is no doubt that the optimization process improves the results of the characterization.

**Table 10-V.** Color differences ($\Delta E^*_{94}$ and CIEDE2000) from the measured values using the optimization technique.

<table>
<thead>
<tr>
<th></th>
<th>average $\Delta E^*_{94}$</th>
<th>standard deviation $\Delta E^*_{94}$</th>
<th>maximum $\Delta E^*_{94}$</th>
<th>RGB ramp and gray scale data</th>
<th>Validation data</th>
<th>Dark validation data</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGB ramp and gray scale data</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.4</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>validation data</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>dark validation data</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Table 10-VI.** Color differences ($\Delta E^*_{94}$ and CIEDE2000) from the measured values without the optimization.

<table>
<thead>
<tr>
<th></th>
<th>average $\Delta E^*_{94}$</th>
<th>standard deviation $\Delta E^*_{94}$</th>
<th>maximum $\Delta E^*_{94}$</th>
<th>RGB ramp and gray scale data</th>
<th>Validation data</th>
<th>Dark validation data</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGB ramp and gray scale data</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>1.4</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>validation data</td>
<td>0.5</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>dark validation data</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Figure 10-5 shows a histogram of color differences for the red, green, and blue ramp data, as well as the gray scale data. Figures 10-6 and 10-7 show similar graphs for the validation data sets. These figures show that color differences for all parts of the data set are very low.
Figure 10-5. Histogram of color differences for gray scale/ramp data sets.

Figure 10-6. Histogram of color differences for the full 0-255 validation data set.
When the results of the model were compared to those of Wyble and Fairchild (1998), and Calabria (2002), the model in this research performed comparably or better in all tasks.

Other results within this research were compared. Figure 10-8 shows a flowchart of how these comparisons were made. A similar flowchart of characterization analysis can be seen in Taplin’s work (2001). First, the digital counts displayed were measured in tristimulus space. These were compared to the estimated tristimulus values that were predicted from the forward model that was based on the original measurements. This is called the forward model prediction error. The color differences for this type of error were previously shown in Table 10-V. The purpose of this comparison is to check how well the forward model performs. Next, the measured tristimulus values were sent
through the inverse model to obtain *reproduction measured digital counts*, which were then displayed and measured to obtain *reproduction measured tristimulus values*. These were compared to the original measured tristimulus values for an *end-to-end performance evaluation*. The purpose of this comparison is to check how well the entire characterization performs, since the inverse model is a result of the forward model created in the characterization. The *reproduction measured digital counts* were also sent through the forward model to obtain *reproduction predicted tristimulus values*. These were compared to the *reproduction measured tristimulus values* to obtain a *model estimate error*. The purpose of this comparison is to check the error between the forward and inverse models.

![Flowchart of experimental comparisons.](image)

Tables 10-VII and 10-VIII show the color difference values for these comparisons. The end-to-end performance of this characterization is quite good with average and maximum CIEDE2000 values of 0.1 and 0.5, respectively, for the validation data set and similar results for the ramp data and dark validation set.
Table 10-VII. Color differences ($\Delta E^{*}_{ab}$) for various comparisons within this research.

<table>
<thead>
<tr>
<th>Spectral Comparison</th>
<th>ramp &amp; gray scale</th>
<th>validation (0-255)</th>
<th>dark validation (0-25)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ave</td>
<td>std dev</td>
<td>max</td>
</tr>
<tr>
<td>Model Estimation Error</td>
<td>0.1</td>
<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>End-to-End Performance</td>
<td>0.1</td>
<td>0.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 10-VIII. Color differences (CIEDE2000) for various comparisons within this research.

<table>
<thead>
<tr>
<th>Spectral Comparison</th>
<th>ramp &amp; gray scale</th>
<th>validation (0-255)</th>
<th>dark validation (0-25)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ave</td>
<td>std dev</td>
<td>max</td>
</tr>
<tr>
<td>Model Estimation Error</td>
<td>0.2</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>End-to-End Performance</td>
<td>0.2</td>
<td>0.2</td>
<td>0.7</td>
</tr>
</tbody>
</table>

The measurements used in the characterization were repeated using both the PR-650 and Minolta instruments, previously described in the equipment and procedure section. The transformation matrices that were optimized using the measurements from these two instruments are shown in Equations 10-4 and 10-5, respectively for the PR-650 and Minolta instruments.

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
41.61 \\
22.24 \\
0.20
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B
\end{bmatrix} + \begin{bmatrix}
5.90 \\
9.67 \\
19.61
\end{bmatrix} \begin{bmatrix}
0.21 \\
0.29 \\
0.08
\end{bmatrix}
\quad (10-4)
\]

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
51.47 \\
27.02 \\
0.44
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B
\end{bmatrix} + \begin{bmatrix}
29.98 \\
62.66 \\
6.10
\end{bmatrix} \begin{bmatrix}
11.53 \\
10.86 \\
57.37
\end{bmatrix} \begin{bmatrix}
0.45 \\
0.47 \\
0.36
\end{bmatrix}
\quad (10-5)
\]

The results of these repeated characterizations are shown in Tables 10-IX and 10-X.
Table 10-IX. Color differences ($\Delta E^*_{94}$ and CIEDE2000) from the measured values using the optimization technique and PR-650 instrument measurements.

<table>
<thead>
<tr>
<th></th>
<th>average $\Delta E^*_{94}$</th>
<th>CIEDE2000</th>
<th>standard deviation $\Delta E^*_{94}$</th>
<th>CIEDE2000</th>
<th>maximum $\Delta E^*_{94}$</th>
<th>CIEDE2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGB ramp and gray scale data validation data</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>dark validation data</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 10-X. Color differences ($\Delta E^*_{94}$ and CIEDE2000) from the measured values using the optimization technique and Minolta instrument measurements.

<table>
<thead>
<tr>
<th></th>
<th>average $\Delta E^*_{94}$</th>
<th>CIEDE2000</th>
<th>standard deviation $\Delta E^*_{94}$</th>
<th>CIEDE2000</th>
<th>maximum $\Delta E^*_{94}$</th>
<th>CIEDE2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGB ramp and gray scale data validation data</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
<td>0.4</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td>dark validation data</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.7</td>
<td>0.9</td>
</tr>
</tbody>
</table>

The results of the characterization using the PR-650 compare well to the initial results using the LMT instrument. The color differences are basically the same, and within the limits of the visual threshold. While the results for the Minolta instrument are not as good as for the other two instruments, they are still more than acceptable for a good quality characterization. Only the maximum color differences are slightly beyond the visual threshold. However, in most images, especially complex scenes, this slightly larger color error would not be greatly perceived.

10.1.3 Conclusions

In summary, an Apple Cinema liquid crystal display was characterized with a “native” gamma setting, 100% brightness, and an uncorrected white point. The forward model was constructed using three one-dimensional LUTs and a $(3 \times 4)$ primary matrix. A technique described in Berns, et al. for optimizing the flare values was used to optimize both the primary matrix and the flare values, simultaneously (Berns, 2002). As an enhancement, the LUTs were dynamically updated as the matrix was optimized.
Using the LMT illuminance colorimeter, the average CIEDE2000 value for the validation data set was 0.1. The maximum color difference value of the validation set was 0.4 CIEDE2000. The second validation set, consisting only of dark colors, had color difference values of 0.1 and 0.3 for the average and maximum values, respectively, showing that darker colors do not hinder the characterization process. The end-to-end performance of this characterization performed comparably to the performance of the forward model.

The monitor’s primaries, as well as channel independence, were evaluated and seem excellent for this monitor. In addition, spatial dependence and uniformity of this monitor are also excellent. Comparisons between the results for this monitor and Wyble/Fairchild's results for a similar monitor, showed that the Apple Cinema Display used in this research is probably superior to that of Wyble/Fairchild's LCD display. The results of this research are comparable to Calabria's results of his characterization for the same monitor.

Finally, the characterization was performed with two more instruments, the PR-650 radiometer and the Minolta colorimeter. The results of the characterization using these two instruments compare well to those using the LMT instrument. Since the both instruments have a much smaller aperture than the LMT instrument, the comparable results show that the aperture size did not greatly affect the results of this LCD characterization. The comparable results of the Minolta instrument show that even a less
sophisticated instrument that is often used in industry can achieve relatively high-performance results.
10.2 Appendix Two: Quantix Camera Characterization

A Quantix monochrome camera with a Kodak KAF6303E 2-D array CCD was characterized for use as a component of the MVSI imaging system in this research. The Certificate of Performance, provided by the CCD manufacturer, as well as similar previously performed experiments on this and other cameras, are the basis and starting point for the experiments described here. The methods used are described in two unpublished papers where the Roper Scientific SenSys 1602E CCD digital camera was characterized (Rosen, 2000; Taplin, 2000), as well as Shin’s previous publication (2001) on the characterization of the Quantix. The experiments performed include characterizing image latency, linearity, gain, noise, dark current, and spectral sensitivity.

10.2.1 General Experimental Procedure

Procedural details and equipment that are unique to a given experiment will be described under that experimental section.

All experiments were performed with the Quantix monochrome CCD camera, model A00K6016, with a Nikon 50 mm lens. The Grade 3 CCD in the Quantix camera is a Kodak KAF6303E, which was tested in accordance with applicable Roper Scientific procedures. The resolution of the CCD is 3072 x 2048. Table 10-XI gives the details of the Certificate of Performance from Roper Scientific, which the current experiments were compared to. In addition, the dark current is 0.051 electrons/pixel/second at a CCD temperature of -20°C Celsius.
Table 10-XI. Certificate of Performance from Roper Scientific

<table>
<thead>
<tr>
<th>Readout Speed</th>
<th>Gain Setting</th>
<th>Measured Gain (electrons/ADU)</th>
<th>Noise (electrons/RMS)</th>
<th>% Linearity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MHz</td>
<td>1 (0.5 X)</td>
<td>40.0</td>
<td>44.0</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>2 (1 X)</td>
<td>22.0</td>
<td>24.3</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>3 (4 X)</td>
<td>5.3</td>
<td>16.4</td>
<td>0.1</td>
</tr>
<tr>
<td>5 MHz</td>
<td>1 (0.5 X)</td>
<td>41.2</td>
<td>43.2</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>2 (1 X)</td>
<td>21.4</td>
<td>27.8</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>3 (4 X)</td>
<td>5.2</td>
<td>19.8</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The latency experiment and linearity, noise, gain and dark current experiments were performed with the camera at a distance of 42 cm from the subject plane, which was a copy stand surface on "transmissive" mode (light diffused by a relatively uniform white plastic surface). The lens was set to an f-stop of f/11. Kodak neutral density filters, totaling ND 3.5, were used to cut down on light and lengthen exposures. Figure 10-9 shows the set-up for this experiment.
10.2.2 Image Latency

This experiment tested the latency effects of the CCD. Latency is the effect of the CCD not being completely “cleared” after one exposure so that the mean digital counts of the new image are higher than they would be if the CCD had been completely cleared.

The Quantix has a “clear count” mode to set the number of times the CCD should be cleared before a new exposure is taken. This mode was set to 2 for this experiment. In addition, the “ADC offset” was set to 2760 and the camera “mode” was set to “pre-exposure”. The “gain” was set to 2 and the “speed” was set to 5 MHz.

A saturated exposure was taken followed by a dark image (with the shutter closed) at a known time interval from the light exposure. This was repeated 10 subsequent times with...
an increased delay between dark and light images each time. Table 10-XII shows the numerical results of this experiment.

<table>
<thead>
<tr>
<th>Time Delay (seconds)</th>
<th>Minimum (digital counts)</th>
<th>Maximum (digital counts)</th>
<th>Mean (digital counts)</th>
<th>Deviation (digital counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>55</td>
<td>4095</td>
<td>61.74</td>
<td>5.08</td>
</tr>
<tr>
<td>50</td>
<td>55</td>
<td>4095</td>
<td>61.79</td>
<td>5.08</td>
</tr>
<tr>
<td>75</td>
<td>55</td>
<td>4095</td>
<td>61.62</td>
<td>5.08</td>
</tr>
<tr>
<td>100</td>
<td>55</td>
<td>4095</td>
<td>61.59</td>
<td>5.08</td>
</tr>
<tr>
<td>125</td>
<td>55</td>
<td>4095</td>
<td>61.50</td>
<td>5.08</td>
</tr>
<tr>
<td>150</td>
<td>54</td>
<td>4095</td>
<td>61.14</td>
<td>5.08</td>
</tr>
<tr>
<td>175</td>
<td>54</td>
<td>4095</td>
<td>60.99</td>
<td>5.08</td>
</tr>
<tr>
<td>200</td>
<td>54</td>
<td>4095</td>
<td>61.14</td>
<td>5.09</td>
</tr>
<tr>
<td>225</td>
<td>54</td>
<td>4095</td>
<td>60.97</td>
<td>5.09</td>
</tr>
<tr>
<td>250</td>
<td>54</td>
<td>4095</td>
<td>60.99</td>
<td>5.08</td>
</tr>
</tbody>
</table>

Figure 10-10 shows the mean pixel value versus the time delay before the dark exposure. It is obvious that while there is a slight downward trend, the change in mean values is so small that this so-called "latency", here, could be just random noise. If there is any actual latency, it is probably so slight that it would not affect our experiments.
10.2.3 Linearity, Gain, Noise, and Dark Current

Since very little, if any, latency was found, no time delay was used in this experiment. L. Taplin and F. Imai wrote the software used to control the camera for the experiment, which captured two dark images and then two light images for each exposure time. This was repeated for nominal gain settings of 1, 2, and 3, as well as speeds of 1 and 5 MHz. Therefore, since the software incorporated a loop to repeat the exposures for the three gain settings, it only had to be run twice (once for each speed setting). The exposure times for each gain setting are shown in Table 10-XIII.
Table 10-XIII. Exposure times used for experiment 2 for different gain settings.

<table>
<thead>
<tr>
<th>Gain 1 (time in seconds)</th>
<th>Gain 2 (time in seconds)</th>
<th>Gain 3 (time in milliseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>2.5</td>
<td>2.5</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>250</td>
</tr>
<tr>
<td>7.5</td>
<td>7.5</td>
<td>500</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>750</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>1000</td>
</tr>
<tr>
<td>14</td>
<td>14</td>
<td>1250</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>1500</td>
</tr>
<tr>
<td>18</td>
<td>18</td>
<td>1750</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td>22</td>
<td>22</td>
<td>2250</td>
</tr>
<tr>
<td>24</td>
<td>24</td>
<td>2500</td>
</tr>
<tr>
<td>26</td>
<td>26</td>
<td>2750</td>
</tr>
<tr>
<td>28</td>
<td>28</td>
<td>3000</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>3250</td>
</tr>
<tr>
<td>35</td>
<td>35</td>
<td>3500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3750</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4000</td>
</tr>
</tbody>
</table>

For each image, the mean, minimum, maximum, and variance were calculated. For each of the two light images and the two dark images for each gain setting, the standard deviation of the difference between the light images was computed. For each exposure time at each gain setting, the signal variance was calculated.

Figure 10-11 shows the signal linearity for the three gain settings for a speed of 5 MHz, using the first light image in each set. At a mean of 4095, the images begin clipping. Figure 10-12 shows the same graph with best-fit linear lines. Similar graphs were made for the 1 MHz speed setting; however, their similarity to the 5 MHz graphs makes them redundant.
Figure 10-11. Gain Linearity of Quantix CCD at three gain settings for speed of 5 MHz.

Figure 10-12. Gain Linearity of Quantix CCD with best-fit lines at three gain settings for speed of 5 MHz.
Gain defines the number of electrons recorded by the CCD as compared to the number of digital counts in the image. It is obvious that as the gain setting increases, the mean of the images grows increasingly faster. In other words, the slopes are greater with greater gain settings. This is true for both speed settings. With $R^2$ values that are so close to unity, it is obvious that the gain of this CCD is very linear. The number of electrons it takes to produce the image increases linearly with respect to the number of digital counts that are actually in the image.

Figure 10-13 shows the signal variance for a speed 5 MHz. Again, the 1 MHz equivalent is redundant. This plot shows that the variance increases linearly for a particular exposure range at each gain setting. Figure 10-14 shows this linear relationship for 5 MHz. Table 10-XIV shows the results of the gain and signal noise calculations and their comparison to the specifications of the Certificate of Performance. The gain is calculated as the inverse of the slope of the gain-noise graphs for each gain value. The signal noise is calculated as the y-intercept of the signal variance for a given gain value.
Figure 10-13. Signal Variance of Quantix CCD for speed of 5 MHz.

Figure 10-14. Image noise and gain of Quantix CCD for speed of 5 MHz.
Table 10-XIV. The gain and noise calculations compared to the Certificate of Performance specifications. Gain is defined as electrons/ADU and noise is defined as electrons/RMS.

<table>
<thead>
<tr>
<th>Speed</th>
<th>Gain Setting</th>
<th>Calculated Gain</th>
<th>Certificate Specs Gain</th>
<th>Gain Difference</th>
<th>Calculated Noise</th>
<th>Certificate Specs Noise</th>
<th>Noise Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MHz</td>
<td>1</td>
<td>41.0</td>
<td>40.0</td>
<td>1.0</td>
<td>1.7</td>
<td>44.0</td>
<td>-42.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>20.8</td>
<td>22.0</td>
<td>-1.2</td>
<td>4.8</td>
<td>24.3</td>
<td>-19.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.0</td>
<td>5.3</td>
<td>-0.3</td>
<td>13.7</td>
<td>16.4</td>
<td>-2.7</td>
</tr>
<tr>
<td>5 MHz</td>
<td>1</td>
<td>44.8</td>
<td>41.2</td>
<td>3.6</td>
<td>4.5</td>
<td>43.2</td>
<td>-38.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>22.4</td>
<td>21.4</td>
<td>1.0</td>
<td>5.4</td>
<td>27.8</td>
<td>-22.4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.0</td>
<td>5.2</td>
<td>-0.2</td>
<td>17.0</td>
<td>19.6</td>
<td>-2.6</td>
</tr>
</tbody>
</table>

Evaluating Table 10-XIV, the difference in gain between our calculations and the known values is very small. The reason for the large difference in noise is likely differences in methods, since Roper Scientific’s experimental set-up and procedures are unknown and likely different than ours.

The dark current, as quoted on the CCD specifications sheet, is 0.051. This value is not dependant on the gain setting, only on temperature. Table 10-XV shows the calculated dark current for the different gain/speed combinations, as well as for both the dark current image sets. This was calculated by taking the slope of the dark current plots, multiplying by appropriate gain values, and then dividing by the integration time.

Table 10-XV. The dark current (electrons/pixel/second) compared to the Certificate of Performance specification for dark current at a temperature of -20°C Celsius.

<table>
<thead>
<tr>
<th>Speed</th>
<th>Gain</th>
<th>Dark Current</th>
<th>Certificate Specs</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 MHz</td>
<td>1</td>
<td>4.48 x 10^-5</td>
<td>0.051</td>
<td>-0.051</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.98 x 10^-5</td>
<td>0.051</td>
<td>-0.051</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.51 x 10^-5</td>
<td>0.051</td>
<td>-0.051</td>
</tr>
</tbody>
</table>

It is very obvious that the calculated dark current is very small compared to the Certificate of Performance. This shows that the dark current is actually much better than specified. Figure 10-15 shows that from 10 seconds to 10 minutes, the dark current does not increase greatly (for a speed of 5 MHz). Measurement uncertainty is probably the
source of the small amount of variability that exists. The large discrepancy in results can probably be attributed to a difference in camera settings when the experiment was performed. For example, the CCD was cleared twice between each exposure for our experiment and may not have been for the Roper Scientific experiments. This might cause more dark current in their results over time, if this is the case.

![Dark Current for 5 MHz graph](image)

*Figure 10-15. Dark Current Linearity of Quantix CCD for speed of 5 MHz.*

### 10.2.4 Accuracy of Monochromator

Measuring spectral sensitivity requires a calibrated monochromator. The accuracy of the Optronics single grating monochromator was verified. To accomplish this, a mercury-cadmium light source was used because the lines in the spectrum are known. A model 730a Optronic Laboratories, Inc. radiometer was used in this experiment with a D1-730-5C silicon photo detector. Several lines were measured and their peaks found. These
peaks were compared to the known peaks of the mercury and cadmium sources. Figure 10-16 shows the experimental set-up for this experiment and Table 10-XVI shows the results.

Figure 10-16. Experimental set-up for monochromator accuracy experiment.

<table>
<thead>
<tr>
<th>Element</th>
<th>Actual</th>
<th>Measured</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>435.8</td>
<td>435.8</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>546.0</td>
<td>546.5</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>365.0</td>
<td>364.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Cadmium</td>
<td>643.8</td>
<td>643.8</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>508.6</td>
<td>508.6</td>
<td>0</td>
</tr>
</tbody>
</table>

For most of the visible range the wavelength errors are negligible.

A related experiment was performed to check the bandwidth of the monochromator with 2.5 mm entrance and exit slits. The mercury peak at 435.8 nm was used. Measurements were taken from 420 to 450 nm, centered approximately on the known peak. Figure 10-17 shows these measurements. The shorter green line shows the full width at half height, which extends from approximately 432 to 442 nm, making the bandwidth approximately 10 nm by visual inspection.
Figure 10-17. Radiance measurements of a mercury peak. The longer green line shows the approximate top of this peak and the shorter green line shows the "full width at half height". This shows a bandwidth of approximately 10 nm.

10.2.5 Camera Spectral Sensitivity

The Quantix was used to capture images of a light source at different wavelengths. At the same time, a spectroradiometer was used to obtain spectral radiance measurements of the light source. This was done for both xenon and tungsten light sources.

The first light source was an Ernst Leitz GMBH Wetzler xenon lamp with a model XLZ-1A-M10 power source of the same brand name. The second was an Optronic Laboratories, Inc. lamp, model 740-20, with a Hewlett-Packard Harrison 6274A DC power supply, Hewlett-Packard 34740A DC voltmeter set at 0.6 amperes and a 1-ohm resistor, and a General Electric tungsten bulb, model Q6.6A/T3/CL 100M. The spectral
power distributions for these light sources were normalized at 560 nanometers and are shown in Figure 10-18. The xenon lamp was of much higher luminance than the tungsten lamp. For this reason, the measurements using the tungsten took much longer than those using the xenon lamp.

An Optronics Laboratories, Inc. single grating monochromater model 40A with 2.5 mm entrance and exit slits and a 10 nm bandpass was controlled by a model 740-1C controller of the same brand and software written by L. Taplin. The light was focused onto halon pressed to 1 g/cm³.
The spectral sensitivities, as measured here, are a combination of the camera, the 50 mm lens, and an infrared cut-off filter. While the entire CCD was imaged, the image of the halon covered the center of the CCD, and approximately 30 pixels square within this area were used for the statistics (statistics software written by F. Imai in MatLab). The exact coordinates used were 1575, 870 (top left) - 1605, 900 (bottom right).

The images were taken at every 10 nanometers with a gain of 2 for a constant exposure time of 1,400 milliseconds for the xenon lamp and 13,000 milliseconds for the tungsten lamp. The lens was set to f/11 and f/5.6, respectively. At the same time, radiance measurements were taken at every 10 nanometers. Figure 10-19 shows the experimental set-up for this part of the experiment (including the xenon light source). A desktop computer held the software (written in Basic by L. Taplin) to control the monochromator and a field computer controlled the Quantix camera using V++ version 4.0 on a Windows 2000 platform.

Figure 10-19. Spectral sensitivity experimental set-up.
Once all the images were obtained, statistics were calculated, including mean, maximum, minimum, and standard deviation for the image's digital counts. Figure 10-20 shows the mean digital counts for the entire set of images for both light sources.

Next, the spectral sensitivity of the system was calculated by dividing the mean (with the dark current subtracted) by the radiance. These values were normalized and are shown in Figure 10-21 along with Roper Scientific/Kodak’s results (same data) for the quantum efficiency of the 6303E CCD. This is shown by the black data set in the plot.
The data sets are very similar. Unfortunately, there are some small differences between the xenon and tungsten measurements. The discrepancy in the tungsten measurement could be a result of the extremely low blue content in its spectral power distribution. This could have resulted in measurements with a large amount of noise in the shorter wavelengths. This shows that spectral sensitivities measured with a tungsten light source may be unreliable, and that the xenon might be a better choice for such measurements. Therefore, the xenon sensitivities were assumed to be more approximately correct and were averaged. The averaged spectral sensitivities are shown in Figure 10-22. The spectral data are tabulated in Table 10-XVII. In the future, these data will be used for all simulations involving this combination of camera and CCD.
Figure 10-22. Normalized average spectral sensitivities.
Table 10-XVII. Average spectral sensitivities of Quantix camera with 50mm lens and Unaxis Balzor broadband near IR reduction filter (model UBO-11RE) using a Xenon light source.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Spectral Sensitivities</th>
<th>Wavelength (nm)</th>
<th>Spectral Sensitivities</th>
</tr>
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<td>0.78</td>
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</tr>
<tr>
<td>550</td>
<td>0.77</td>
<td>730</td>
<td>0.23</td>
</tr>
</tbody>
</table>
10.3 Appendix Three: MATLAB Code

**Graphical User Interface**

```matlab
% make_all_pairs - creates a text file with randomly ordered images for psychophysical experiment
% IMPORTANT: Only needs to be run once
% only need to rerun this program if number of images gets changed
% create "all_pairs.txt" text file with all possible image pairs for experiment
% inputs: none
% outputs: image data
% functions called: none
% Written by Lawrence Taplin 7/22/02
% last updated 9/10/02
% number of images per set
image_counts = [7 7 7 7 6 6 6 6];
all_pairs = [];
j=1;
for i=1:length(image_counts)
    new_pairs = nchoosek(j+image_counts(i)-1,2);
    all_pairs = [all_pairs;new_pairs;repmat(i,size(new_pairs,1),1)];
    j = j+image_counts(i);
end
% write out results to a file
save('Fechner2:Ellen:Experiment:all_pairs.txt','all_pairs','-ascii');
```

```matlab
% prelim_gui - gui to input user data for psychophysical experiment
% inputs: change.obs = number of observers
% change.n = number of images
% change.height = height of images
% change.width = width of images
% outputs: none
% functions called: prelim callbacks
% Written by Ellen A. Day 4/19/02
% last updated 7/9/02

function prelim_gui
    % STUFF THAT CAN BE CHANGED %%%%%
    change.obs = 18;
    change.n = 228;
    change.height = 512;
    change.width = 768;
    %%%%%
    % creates a figure without the default menubar
    Hf_1 = figure('menubar',menubar);
    % sets the size of the window to the size of the screen
    set(Hf_1,'Position',[100 400 150 270]);
    % stores the structure in Hf_1
```
set(Hf_1,'UserData',change);

% creates editable text boxes for user to input initials & age
Hc_2 = uicontrol('Style','edit','Position',[30,220,100,20]);
set(Hc_2,'Tag','initials');
Hc_25 = uicontrol('Style','text','String','Initials','Position',[30,240,100,20],'BackgroundColor',[0.8 0.8 0.8]);
Hc_3 = uicontrol('Style','edit','Position',[30,170,100,20]);
set(Hc_3,'Tag','age');
Hc_35 = uicontrol('Style','text','String','Age','Position',[30,190,100,20],'BackgroundColor',[0.8 0.8 0.8]);

% creates radio button for user to choose male/female
Hc_41 = uicontrol('Style','radiobutton','Position',[55,120,100,20],'Value',1,'Tag','sexM');
Hc_42 = uicontrol('Style','radiobutton','Position',[90,120,100,20],'Value',0,'Tag','sexF');
set(Hc_41,'callback','mutual_exclude("sexF")');
set(Hc_42,'callback','mutual_exclude("sexM")');

% creates radio button for user to choose expert/naive
Hc_51 = uicontrol('Style','radiobutton','Position',[55,50,100,20],'Value',1,'Tag','expert');
Hc_52 = uicontrol('Style','radiobutton','Position',[90,50,100,20],'Value',0,'Tag','naive');
set(Hc_51,'callback','mutual_exclude("naive")');
set(Hc_52,'callback','mutual_exclude("expert")');

% button to close file
Hc_6 = uicontrol('Style','pushbutton','String','Done','Position',[30,0,100,20],'CallBack','prelim_callbacks');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%#
% prelim_callbacks - callbacks for prelim_gui
% inputs: none
% outputs: initials and change.n into image_display_gui
% functions called: image_display_gui
% Written by Ellen A. Day 4/20/02
% last updated 6/24/02
% function prelim_callbacks
% get variable data from structure
change = get(gcbf,'UserData');
% finds the text boxes and gets their contents
Hc_2 = findobj('Tag','initials');
initials = get(Hc_2,'String');
Hc_3 = findobj('Tag','age');
age = get(Hc_3,'String');

% figures out which radiobuttons were chosen
sex = get(Hc_41,'Value');
if sex == 1
    sex = 'male';
else
    sex = 'female';

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%#

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Hc_51 = findobj('Tag', 'expert');
expertise = get(Hc_51, 'Value');

if expertise == 1
    expertise = 'expert';
else
    expertise = 'naive';
end

% creates and opens a file with append permissions
fid = fopen(sprintf('Fechner 2:Ellen:Experiment:ObserverData:%s_data.txt', initials), 'a');
% prints the user data to the file
file = fprintf(fid, '%s %s %s %s
', initials, age, sex, expertise);
% closes the file
fclose(fid);

% read in the image pairs from file
orig = load('Fechner 2:Ellen:Experiment:all_pairs.txt');

% create random order
use_order = zeros(size(orig));
for i = 1:max(orig(:,3))
    % find the images that go with this target
    list = find(orig(:,3) == i);
    % randomize the list
    [blah, rorder] = sort(rand(length(list), 1));
    % copy the original data
    orig_temp = orig(list,:);
    % store the randomized order
    use_order(list,:) = orig_temp(rorder,:);
end

% randomly swap the images left and right
toswap = find(rand(size(orig,1),1) < 0.5);
temp = use_order(toswap,1);
use_order(toswap,1) = use_order(toswap,2);
use_order(toswap,2) = temp;

% writes file with user's image order
% creates and opens a file with append permissions
fid = fopen(sprintf('Fechner 2:Ellen:Experiment:ObserverData:%s_order.Ut,iniUalU,als.txt', initials), 'w');
% prints the user data to the file
for i = 1:size(use_order,1)
    file = fprintf(fid, '%d %d %d
', use_order(i,1), use_order(i,2), use_order(i,3));
end
% closes the file
fclose(fid);
% closes current figure
close(gcf);
% runs experiment
image_display_gui(initials, change.n);
%******************************************************************************
% image_display_gui - gui for psychophysical experiment
% % % inputs: initials = initials of observer
% % n = number of images
%
% outputs: displayed images
% % functions called: read_images
% gui_callback with choice of image (1 or 2)
% %
% Written by Ellen A. Day 4/8/02
% last updated 6/24/02

function image_display_gui(initials,n)

% read in the images
exp_data.images = read_images;

% number of image pairs
num_pairs = n;

% gets the size of the current screen
screen_size = get(0,'ScreenSize');

% creates a figure without the default menubar
Hf_1 = figure('menubar','menubar');

% set gray background
% DAYLIGHT
set(gcf,'Color',[0.5662 0.5749 0.7322]);
% INCANDESCENT A
% set(gcf,'Color',[0.8936 0.7194 0.5414]);

% sets the size of the window to the size of the screen
set(Hf_1,'Position',screen_size);

% control left/right mouse-clicks
set(Hf_1,'KeyPressFcn','gui_callback(1)');
set(Hf_1,'WindowButtonDownFcn','gui_callback(2)');

% load text file with image order
exp_data.user = initials;
exp_data.order = load(sprintf('Fechner2:Ellen:Experiment:ObserverData:%s_order.txt',exp_data.user));
exp_data.pair = 1;
exp_data.num_pairs = num_pairs;

% stores structure
set(Hf_1,'UserData',exp_data);

Hp_1 = subplot(1,2,1);
Hp_1 = subplot('position',[0.02 0.25 0.48 0.5]);
Hi_1 = subimage(exp_data.images(:,:,exp_data.order(exp_data.pair,1)));
% get size that image is actually being displayed at
% get(Hi_1,'XData')
% get(Hi_1,'YData')
set(Hi_1,'Tag','Image1');
axis off;

Hp_2 = subplot(1,2,2);
Hp_2 = subplot('position',[0.52 0.25 0.48 0.5]);
Hi_2 = subimage(exp_data.images(:,:,exp_data.order(exp_data.pair,2)));
% get size that image is actually being displayed at
% get(Hi_2,'XData')
% get(Hi_2,'YData')
set(Hi_2,'Tag','Image2');
axis off;

% gui_callback - displays text and closes window
% inputs: which_image = '1' or '2' for image choice
% outputs: none
% functions called: write_file
function gui_callback(which_image)

    % retrieve the structure with all experimental data including images order
    exp_data = get(gcbf,'UserData');

    % write the file with the users initials, the 1st and 2nd images, and the image the user chooses, respectively
    write_file(exp_data.user, exp_data.order(exp_data.pair,1), exp_data.order(exp_data.pair,2), which_image);

    % increment pair number
    exp_data.pair = exp_data.pair + 1;

    % resolve experimental data back into UserData structure
    % gcbf = get callback figure
    set(gcbf, 'UserData', exp_data);

    if exp_data.pair <= exp_data.num_pairs

        % check if the target has changed since the last image
        if exp_data.order(exp_data.pair,3) ~= exp_data.order(exp_data.pair-1,3);
            msgbox(sprintf('Please Change the Target to %d.',exp_data.order(exp_data.pair,3)),'STOP!!!!','wam','modal');
        end

        % display white noise images for 1 second
        [m,n,c] = size(exp_data.images(:,:,exp_data.order(exp_data.pair,1))); noise = repmat(uint8(rand(m,n)*255),[1,1,c]);
        noise(:,:,1) = (rand(m,n)*144);
        noise(:,:,2) = (rand(m,n)*147);
        noise(:,:,3) = (rand(m,n)*187);
        display_images(noise,
        % display next pair of images
        display_images(exp_data.images(:,:,exp_data.order(exp_data.pair,1)),exp_data.images(:,:,exp_data.order(exp_data.pair,2)));
        end

% read_images - reads in images for psychophysical experiment

function image_data = read_images

    % read the images
    % progress bar
    h = waitbar(0,'Please wait...');

    % inputs: images
    % outputs: image data
    % functions called: none

    % Written by Ellen A. Day 4/17/02
    % last updated 9/10/02

    image_data(:,:,1) = imread('Fechner2:Ellen:Experiment:Images:D-nature1.tif');
    image_data(:,:,2) = imread('Fechner2:Ellen:Experiment:Images:D-nature2.tif');
    image_data(:,:,3) = imread('Fechner2:Ellen:Experiment:Images:D-nature3.tif');
    image_data(:,:,4) = imread('Fechner2:Ellen:Experiment:Images:D-nature4.tif');
    image_data(:,:,5) = imread('Fechner2:Ellen:Experiment:Images:D-nature5.tif');
    image_data(:,:,6) = imread('Fechner2:Ellen:Experiment:Images:D-nature6.tif');
    image_data(:,:,7) = imread('Fechner2:Ellen:Experiment:Images:D-nature7.tif');
h = waitbar(8/100,'8% complete...');

image_data(:,:,8) = imread('Fechner 2:Ellen:Experiment:images:D-baby1.tif');
image_data(:,:,9) = imread('Fechner 2:Ellen:Experiment:images:D-baby2.tif');
image_data(:,:,10) = imread('Fechner 2:Ellen:Experiment:images:D-baby3.tif');
image_data(:,:,11) = imread('Fechner 2:Ellen:Experiment:images:D-baby4.tif');
image_data(:,:,12) = imread('Fechner 2:Ellen:Experiment:images:D-baby5.tif');
image_data(:,:,13) = imread('Fechner 2:Ellen:Experiment:images:D-baby6.tif');
image_data(:,:,14) = imread('Fechner 2:Ellen:Experiment:images:D-baby7.tif');

h = waitbar(16/100,'16% complete...');

image_data(:,:,15) = imread('Fechner 2:Ellen:Experiment:images:D-fruit1.tif');
image_data(:,:,16) = imread('Fechner 2:Ellen:Experiment:images:D-fruit2.tif');
image_data(:,:,17) = imread('Fechner 2:Ellen:Experiment:images:D-fruit3.tif');
image_data(:,:,18) = imread('Fechner 2:Ellen:Experiment:images:D-fruit4.tif');
image_data(:,:,19) = imread('Fechner 2:Ellen:Experiment:images:D-fruit5.tif');
image_data(:,:,20) = imread('Fechner 2:Ellen:Experiment:images:D-fruit6.tif');
image_data(:,:,21) = imread('Fechner 2:Ellen:Experiment:images:D-fruit7.tif');

h = waitbar(24/100,'24% complete...');

image_data(:,:,22) = imread('Fechner 2:Ellen:Experiment:images:D-paint1.tif');
image_data(:,:,23) = imread('Fechner 2:Ellen:Experiment:images:D-paint2.tif');
image_data(:,:,24) = imread('Fechner 2:Ellen:Experiment:images:D-paint3.tif');
image_data(:,:,26) = imread('Fechner 2:Ellen:Experiment:images:D-paint5.tif');
image_data(:,:,27) = imread('Fechner 2:Ellen:Experiment:images:D-paint6.tif');
image_data(:,:,28) = imread('Fechner 2:Ellen:Experiment:images:D-paint7.tif');

h = waitbar(32/100,'32% complete...');

image_data(:,:,29) = imread('Fechner 2:Ellen:Experiment:images:D-ccdc1.tif');
image_data(:,:,30) = imread('Fechner 2:Ellen:Experiment:images:D-ccdc2.tif');
image_data(:,:,31) = imread('Fechner 2:Ellen:Experiment:images:D-ccdc3.tif');
image_data(:,:,32) = imread('Fechner 2:Ellen:Experiment:images:D-ccdc4.tif');
image_data(:,:,33) = imread('Fechner 2:Ellen:Experiment:images:D-ccdc5.tif');
image_data(:,:,34) = imread('Fechner 2:Ellen:Experiment:images:D-ccdc6.tif');
image_data(:,:,35) = imread('Fechner 2:Ellen:Experiment:images:D-ccdc7.tif');

h = waitbar(48/100,'48% complete...');

image_data(:,:,36) = imread('Fechner 2:Ellen:Experiment:images:D-cc1.tif');
image_data(:,:,37) = imread('Fechner 2:Ellen:Experiment:images:D-cc2.tif');
image_data(:,:,38) = imread('Fechner 2:Ellen:Experiment:images:D-cc3.tif');
image_data(:,:,39) = imread('Fechner 2:Ellen:Experiment:images:D-cc4.tif');
image_data(:,:,40) = imread('Fechner 2:Ellen:Experiment:images:D-cc5.tif');
image_data(:,:,41) = imread('Fechner 2:Ellen:Experiment:images:D-cc6.tif');
image_data(:,:,42) = imread('Fechner 2:Ellen:Experiment:images:D-cc7.tif');

h = waitbar(56/100,'56% complete...');

image_data(:,:,43) = imread('Fechner 2:Ellen:Experiment:images:D-full_nature2.tif');
image_data(:,:,44) = imread('Fechner 2:Ellen:Experiment:images:D-full_nature3.tif');
image_data(:,:,45) = imread('Fechner 2:Ellen:Experiment:images:D-full_nature4.tif');
image_data(:,:,46) = imread('Fechner 2:Ellen:Experiment:images:D-full_nature5.tif');
image_data(:,:,47) = imread('Fechner 2:Ellen:Experiment:images:D-full_nature6.tif');
image_data(:,:,48) = imread('Fechner 2:Ellen:Experiment:images:D-full_nature7.tif');

h = waitbar(64/100,'64% complete...');
image_data(:, :, 49) = imread('Fechner:Ellen:Experiment:Images:D_full_baby2.tif');
image_data(:, :, 50) = imread('Fechner:Ellen:Experiment:Images:D_full_baby3.tif');
image_data(:, :, 51) = imread('Fechner:Ellen:Experiment:Images:D_full_baby4.tif');
image_data(:, :, 52) = imread('Fechner:Ellen:Experiment:Images:D_full_baby5.tif');
image_data(:, :, 53) = imread('Fechner:Ellen:Experiment:Images:D_full_baby6.tif');
image_data(:, :, 54) = imread('Fechner:Ellen:Experiment:Images:D_full_baby7.tif');

h = waitbar(72/100, 72% complete...);

image_data(:, :, 55) = imread('Fechner:Ellen:Experiment:Images:D_full_fruit2.tif');
image_data(:, :, 56) = imread('Fechner:Ellen:Experiment:Images:D_full_fruit3.tif');
image_data(:, :, 57) = imread('Fechner:Ellen:Experiment:Images:D_full_fruit4.tif');
image_data(:, :, 58) = imread('Fechner:Ellen:Experiment:Images:D_full_fruit5.tif');
image_data(:, :, 59) = imread('Fechner:Ellen:Experiment:Images:D_full_fruit6.tif');
image_data(:, :, 60) = imread('Fechner:Ellen:Experiment:Images:D_full_fruit7.tif');

h = waitbar(80/100, 80% complete...);

image_data(:, :, 61) = imread('Fechner:Ellen:Experiment:Images:D_full_paint2.tif');
image_data(:, :, 62) = imread('Fechner:Ellen:Experiment:Images:D_full_paint3.tif');
image_data(:, :, 63) = imread('Fechner:Ellen:Experiment:Images:D_full_paint4.tif');
image_data(:, :, 64) = imread('Fechner:Ellen:Experiment:Images:D_full_paint5.tif');
image_data(:, :, 65) = imread('Fechner:Ellen:Experiment:Images:D_full_paint6.tif');
image_data(:, :, 66) = imread('Fechner:Ellen:Experiment:Images:D_full_paint7.tif');

h = waitbar(88/100, 88% complete...);

image_data(:, :, 67) = imread('Fechner:Ellen:Experiment:Images:D_full_cc2.tif');
image_data(:, :, 68) = imread('Fechner:Ellen:Experiment:Images:D_full_cc3.tif');
image_data(:, :, 69) = imread('Fechner:Ellen:Experiment:Images:D_full_cc4.tif');
image_data(:, :, 70) = imread('Fechner:Ellen:Experiment:Images:D_full_cc5.tif');
image_data(:, :, 71) = imread('Fechner:Ellen:Experiment:Images:D_full_cc6.tif');
image_data(:, :, 72) = imread('Fechner:Ellen:Experiment:Images:D_full_cc7.tif');

h = waitbar(94/100, 94% complete...);

image_data(:, :, 73) = imread('Fechner:Ellen:Experiment:Images:D_full_cc2.tif');
image_data(:, :, 74) = imread('Fechner:Ellen:Experiment:Images:D_full_cc3.tif');
image_data(:, :, 75) = imread('Fechner:Ellen:Experiment:Images:D_full_cc4.tif');
image_data(:, :, 76) = imread('Fechner:Ellen:Experiment:Images:D_full_cc5.tif');
image_data(:, :, 77) = imread('Fechner:Ellen:Experiment:Images:D_full_cc6.tif');
image_data(:, :, 78) = imread('Fechner:Ellen:Experiment:Images:D_full_cc7.tif');

h = waitbar(100/100, 'Finished...');

pause(1)

% close progress bar
close all;

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function display_images(image_a, image_b)

% get the object that is tagged 'Image1'
Hi_1 = findobj('Tag','Image1');

% set the picture into the image figure
set(Hi_1, 'cdata', image_a);

% display_images displays 2 images for psychophysical experiment

% inputs: image_a & image_b = left image % right image, respectively
% outputs: next 2 images displayed
% functions called: none

% Written by Ellen A. Day 4/17/02
% last updated 5/30/02

pause(1)
% get the object that is tagged 'Image2'
Hi_2 = findobj('Tag','Image2');

% set the picture into the image figure
set(Hi_2,'cdata',image_b);

%****************************
% mutual_exclude - makes radio buttons mutually exclusive
% NOTE: only works for groups of 2 radio buttons
% % inputs: tag of radio button that was clicked
% % outputs: none
% % functions called: none
% % Written by Lawrence Taplin 6/24/02
% last updated 6/24/02 EAD

function mutual_exclude(tag)
off = findobj(0,'Tag',tag);
set(off,'Value',0);
end

%****************************
% write_file - writes data to a text file
% % inputs: user = observer's initials
%   image1 = left image
%   image2 = right image
%   choice = '1' or '2' for choice of left or right image
% % outputs: file = output text file
% % functions called: none
% % Written by Ellen A. Day 4/18/02
% last update 6/19/02

function file = write_file(user, image1, image2, choice)

fid = fopen(sprintf('Fechner-2:Ellen:Experiment:ObserverResults:%s_exp1.txt',user),'a');

file = fprintf(fid,'%d %d %d
',image1, image2, choice);

fclose(fid);
end

Checking Observer Repeatability

%****************************
% check_consistency - checks intra-observer consistency for a single observer
% % inputs: data - data with results of psychophysical experiment for ONE observer (228 x 3)
%   where column 1 is the left image, column 2 is the right image,
%   and column 3 is the choice (1 for left, 2 for left)
% % outputs: "This observer was consistent X out of 12 times!" - # of times observer was consistent out of 12
% % functions called: none
% % Written by Ellen A. Day 9/13/02
% last update EAD 9/19/02

function check_consistency(data)
% sort the rows of data
data = sortrows(data);

% define duplicate data
dups = [3 4; 10 11; 17 16; 24 25; 31 32; 36 39; 44 45; 50 51; 56 57; 62 63; 68 69; 74 75];

% predefine number of inconsistent trials
consistency = 0;

% find duplicate data
for i = 1:size(dups,1)
    [j,k] = find((data(:,1) == dups(i,1) & data(:,2) == dups(i,2)) | (data(:,1) == dups(i,1) & data(:,2) == dups(i,2)));
    if size(j) == 1
        data(j(1),3) = data(j(2),3);  
        consistency = consistency -1;
    else
        consistency = consistency +1;
    end
end

disp(sprintf('%s %i %s',This observer was consistent ', consistency, ' out of 12 times!'));

% Paired Comparison Analysis

% main_analysis - this is the main program for the paired comparison analysis
% inputs: none
% outputs: normal interval scale, aad test, chi-sq test, degrees of freedom,
% paired comparison plot, confidence intervals
% functions called: compile_data - loads data, illuminant is chosen, edited data is sent back out
% paired_comparision - computes paired comparison calculations
% conf_intervals - computes the confidence intervals for the results of the paired comparison analysis
% plot_data - plots paired comparison data and confidence intervals (error bars) for a given data set
% IMAGES: 1 - D1; 2 - pca6wRGB; 3 - pca6; 4 - pinv6wRGB; 5 - pinv6; 6 - tf_pinv; 7 - RGBpinv
%
% Written by Ellen A. Day 9/16/02
% last update EAD 10/8/02

% plot data if temp == 1
temp = 0;

% number of images for the 2 different experiment types
n_COLOR = 7;
n_IQ = 6;

% User chooses experiment type
n = input('Which experiment type? color(1) \n iq(2)?
');

if n == 1
n = n_COLOR;
else
  n = n_IQ;
end

if n == n_COLOR
  % define the target indices
  idx1 = (1:21); % nature
  idx2 = (22:42); % baby
  idx3 = (43:63); % fruit
  idx4 = (64:84); % paint
  idx5 = (85:105); % CCDC
  idx6 = (106:126); % CC

  % User chooses target
  idx = input('Which target? \n    nature(1) \n    baby(2) \n    fruit(3) \n    paint(4) \n    CCDC(5) \n    CC(6)?
');
  if idx == 1
    idx = idx1;
  elseif idx == 2
    idx = idx2;
  elseif idx == 3
    idx = idx3;
  elseif idx == 4
    idx = idx4;
  elseif idx == 5
    idx = idx5;
  else
    idx = idx6;
  end
else
  % define the target indices
  idx1 = (127:141); % nature
  idx2 = (142:156); % baby
  idx3 = (157:171); % fruit
  idx4 = (172:186); % paint
  idx5 = (187:201); % CCDC
  idx6 = (202:216); % CC

  % User chooses target
  idx = input('Which target? \n    nature(1) \n    baby(2) \n    fruit(3) \n    paint(4) \n    CCDC(5) \n    CC(6)?
');
  if idx == 1
    idx = idx1;
  elseif idx == 2
    idx = idx2;
  elseif idx == 3
    idx = idx3;
  elseif idx == 4
    idx = idx4;
  elseif idx == 5
    idx = idx5;
  else
    idx = idx6;
  end
end

% load, compile, and edit data
[data,IIf,obs] = compile_data(idx);

% run paired comparison analysis
[norm_int_scale] = paired_comparison(data,obs,n);
% calculate confidence intervals
[upper_int,lower_int] = conf_intervals(obs,norm_int_scale);

% calculate error bars equal above and below interval scale
ebars = norm_int_scale-lower_int;

% plot data
if temp == 1
    plot_data(idx1,idx2,idx3,idx4,idx5,idx6,n,n_COLOR,ill,norm_int_scale,ebars);
end

% load_data - loads data from observer files
% inputs: none
% outputs: data - edited data where all duplicates are taken out for daylight illuminant
% dataA - edited data where all duplicates are taken out for incandescent A illuminant
% functions called: none
% Written by Ellen A. Day 9/16/02
% last update EAD 10/8/02

function [data, dataA] = load_data

% load Daylight data
data(:,:,1) = load('abc_exp1.txt');
data(:,:,2) = load('cxl_exp1.txt');
data(:,:,3) = load('dcd_exp1.txt');
data(:,:,4) = load('drw_exp1.txt');
data(:,:,5) = load('ead_exp1.txt');
data(:,:,6) = load('efh_exp1.txt');
data(:,:,7) = load('emj_exp1.txt');
data(:,:,8) = load('fhi_exp1.txt');
data(:,:,9) = load('hxz_exp1.txt');
data(:,:,10) = load('jll_exp1.txt');
data(:,:,11) = load('jxk_exp1.txt');
data(:,:,12) = load('lal_exp1.txt');
data(:,:,13) = load('mdf_exp1.txt');
data(:,:,14) = load('mxj_exp1.txt');
data(:,:,15) = load('mxn_exp1.txt');
data(:,:,16) = load('nxj_exp1.txt');
data(:,:,17) = load('oxt_exp1.txt');
data(:,:,18) = load('qxs_exp1.txt');
data(:,:,19) = load('rap_exp1.txt');
data(:,:,20) = load('rsb_exp1.txt');
data(:,:,21) = load('shp_exp1.txt');
data(:,:,22) = load('srf_exp1.txt');
data(:,:,23) = load('sxs_exp1.txt');
data(:,:,24) = load('vii_exp1.txt');
data(:,:,25) = load('xqi_exp1.txt');
data(:,:,26) = load('xxs_exp1.txt');
data(:,:,27) = load('xc_exp1.txt');

% load IncA data
dataA(:,:,1) = load('dcd_exp1-A.txt');
dataA(:,:,2) = load('djc_exp1-A.txt');
dataA(:,:,3) = load('djl_exp1-A.txt');
dataA(:,:,4) = load('drw_exp1-A.txt');
dataA(:,:,5) = load('ead_exp1-A.txt');
dataA(:,:,6) = load('efh_exp1-A.txt');
dataA(:,:,7) = load('emj_exp1-A.txt');
dataA(:,:,8) = load('gmi_exp1-A.txt');
dataA(:,:,9) = load('hxz_exp1-A.txt');
dataA(:,:,10) = load('jll_exp1-A.txt');
dataA(:,:,11) = load('jxk_exp1-A.txt');
dataA(:,:,12) = load('jxk_exp1-A.txt');
dataA(:,:,13) = load('mdf_exp1-A.txt');
dataA(:,:,14) = load('mdf_exp1-A.txt');
function [target, ill, obs] = compile_data(idx);

% choose and load data
[data, dataA] = load_data;
obs_Daylight = 27;
obs_IncA = 27;
% data = input('Which data set do you want to use? (1) male (2) female (3) expert (4) naive (5) ');
if data == 1
    [data, dataA] = load_data;
    obs_Daylight = 27;
    obs_IncA = 27;
elseif data == 2
    [data, dataA] = load_data_male;
    obs_Daylight = 17;
    obs_IncA = 17;
elseif data == 3
    [data, dataA] = load_data_female;
    obs_Daylight = 10;
    obs_IncA = 10;
elseif data == 4
    [data, dataA] = load_data_expert;
    obs_Daylight = 19;
    obs_IncA = 20;
elseif data == 5
    [data, dataA] = load_data_naive;
    obs_Daylight = 8;
    obs_IncA = 7;
end
end
end
end
end

% edit data
for i = 1:size(data, 3)
    temp(:, :, i) = edit_data(data(:, :, i));
end
data = temp;

for i = 1:size(dataA, 3)
    temp2(:, :, i) = edit_data(dataA(:, :, i));
end
dataA = temp2;

clear temp;

ill = input('Which illuminant? Daylight(1) IncA(2)\n');
if ill == 1
    for i = 1:size(data,3)
        target(:,:,i) = [data(idx,:,i)];
    end
    obs = obs_Daylight;
else
    for i = 1:size(dataA,3)
        target(:,:,i) = [dataA(idx,:,i)];
    end
    obs = obs_IncA;
end

% put target data into 2D list
target = permute(target, [1,3,2]);
target = reshape(target, size(target, 1)*size(target, 2), size(target, 3));

% edit data - all duplicates are taken out of data, then data is scaled
% inputs: data - data with results of psychophysical experiment
% where column 1 is the left image, column 2 is the right image,
% and column 3 is the choice (1 for left, 2 for left)
% outputs: data - edited data where all duplicates are taken out, and data is scaled
% functions called: none
% Written by Ellen A. Day 9/13/02
% last update EAD 9/16/02

function [data] = edit_data(data)

% define duplicate data
dups = [3 4; 10 11; 17 18; 24 25; 31 32; 38 39; 44 45; 50 51; 56 57; 62 63; 68 69; 74 75];

% find and remove duplicate data
for i = 1 : size(dups,1)
    [j,k] = find(data(:,1) == dups(i,1) & data(:,2) == dups(i,2));
    if isempty(j)
        [j,k] = find(data(:,1) == dups(i,2) & data(:,2) == dups(i,1));
    end
    if size(j) == [1 1]
        [j,k] = find((data(:,1) == dups(i,2) & data(:,2) == dups(i,1)) | (data(:,1) == dups(i,1) & data(:,2) == dups(i,2)));
        if size(j) == [1 1]
            [j,k] = find((data(:,2) == dups(i,2) & data(:,1) == dups(i,1)) | (data(:,2) == dups(i,1) & data(:,1) == dups(i,2)));
        end
    end
    data = [data(1:j(2)-1,:); data(j(2)+1:end,:)];
end

% scales data to 1-7 for COLOR and 1-6 for IQ
data1 = data(1:21,:); data1 = (data1-7)*6+1;
for i = 2:8
    data(i) = data((i-1)*21+1:(i-1)*21+21,:); data(i) = (data(i)-7)*6+1;
end

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data8 = [(data8(:,1:2)-48) data8(:,3)];
data9 = data(157:171,:);
data10 = data(172:186,:);
data11 = data(187:201,:);
data12 = data(202:216,:);
data13 = data(217:231,:);
data14 = data(232:246,:);
data15 = data(247:261,:);
data16 = data(262:276,:);
data17 = data(277:291,:);
data18 = data(292:306,:);
data19 = data(307:321,:);
data20 = data(322:336,:);
data21 = data(337:351,:);
data22 = data(352:366,:);
data23 = data(367:381,:);
data24 = data(382:396,:);
data25 = data(397:411,:);
data26 = data(412:426,:);
data27 = data(427:441,:);
data28 = data(442:456,:);
data29 = data(457:471,:);
data30 = data(472:486,:);
data31 = data(487:501,:);
data32 = data(502:516,:);

% outputs final data set
data = [data1; data2; data3; data4; data5; data6; data7; data8; data9; data10; data11; data12];

%****************************************************************************************************************************************************
% paired_comparison - computes paired comparison calculations
% inputs: x - data with results of psychophysical experiment
% where column 1 is the left image, column 2 is the right image,
% and column 3 is the choice (1 for left, 2 for left)
% obs - number of observers
% n - number of images
% outputs: norm_int_scale - interval scale of the psychophysical experiment
% functions called: paired_comp_gof_tests - calculates Average Absolute Deviation and Mosteller's Goodness-of-Fit tests
% Written by Ellen A. Day 5/23/02
% last update EAD 6/1/02

function [norm_int_scale] = paired_comparison(x,obs,n)

% number of image pairs
num_pairs = (n*(n-1))/2;

% separate columns
left_image = x(:,1);
right_image = x(:,2);
choice = x(:,3);

% create a matrix that will hold the tally results
freq_matrix = zeros(n,n);

% frequency matrix
for i = 1:size(choice)
    if choice(i) == 1
        freq_matrix(right_image(i),left_image(i)) = freq_matrix(right_image(i),left_image(i)) + 1;
    else
        freq_matrix(left_image(i),right_image(i)) = freq_matrix(left_image(i),right_image(i)) + 1;
    end
end

% add 0.5 to diagonals
% an image is always assumed to be valued the same as itself
diag_prop = repmat(0.5*obs,n,1);
freq_matrix = diag(diag_prop) + freq_matrix;

% calculate proportion matrix
prop_matrix = freq_matrix / obs;

% change proportions to z-scores
% using inverse normal distribution function
% made this a transpose per Ethan's pairedla function
z_matrix = (icdf('Normal',prop_matrix,0,1))';

%****************************************************************************************************************************************************
% This section is taken from Ethan Montag's pairedla function
% takes cares of unanimous decisions
z = [ ];
xmat = [ ];
zeroguy = zeros(1,n);
for i = 1:(n-1)
    for j = (i+1):n
        if isnan(z_matrix(i,j))
            z = [z; z_matrix(i,j)];
            tempguy = zeroguy;
            tempguy(i) = 1; tempguy(j) = -1;
            xmat = [xmat; tempguy];
        end
    end
end
z = [z; 0];
xmat = [xmat; ones(1,n)];
S = inv(xmat' * xmat) * xmat' * z;
norm_int_scale = S - (min(S))
% The above section is taken from Ethan Montag's pairedla function
%******************************************************************************
%%% THIS IS JUST TO CHECK THAT I AM GETTING THE SAME ANSWER AS ETHAN'S FUNCTION
% average columns of z-score matrix
% we will use this as our interval scale
% since we are assuming Thurstone's Case V
% interval_scale = mean(z_matrix');
% normalized interval scale
% norm_int_scale = interval_scale + interval_scale(n)-1
% Do AAD and Mosteller's goodness-of-fit tests
paired_comp_gof_tests(S,n,obs,prop_matrix);
%******************************************************************************

% plot_data - plots paired comparison data and confidence intervals (error bars) for a given data set

% % inputs: idx(0-6) - indices of different targets
%      n - number of images
%      n_COLOR - number of images in color experiment
%      ill - illuminant (daylight = 1; incA = 2)
%      norm_int_scale - interval scale from paired comparison analysis
%      ebars - error bars
% % outputs: plot of given data set
% % functions called: none
% % % IMAGES: 1 - D1; 2 - pca6wRGB; 3 - pca6; 4 - pinwvRGB; 5 - pinv6; 6 - tf_pinv; 7 - RGBpinv
% % Written by Ellen A. Day 10/8/02
% % last update EAD 10/10/02

function plot_data(idx,idx1,idx2,idx3,idx4,idx5,idx6,n,n_COLOR,ill,norm_int_scale,ebars)
  % plot interval scale with error bars
  h1 = figure;
  %plot(norm_int_scale);

  xaxis = 1:n;
  errorbar(xaxis,norm_int_scale,ebars,'.');
  hold on;
  plot(norm_int_scale,'.');
  h2 = findobj(h1,'type','axes')
  %axis([0 8 -0.4 2]);

  % image names
  if n == 7
image_names = {'D1','pca6W','pca6','pinv6W','pinv6','tf_pinv','RGB'}; else
  image_names = {'pca6W','pca6','pinv6W','pinv6','tf_pinv','RGB'};
end

% change the x tick labels to the image types
set(h2,'XTickMode','manual');
if set(h2,'xtick',0:n+1);
set(h2,'xtick',0:n);
set(h2,'xticklabel',image_names{:});
set(h2,'FontSize',10);

% label x axis
xlabel('Image Type');

% label y axis
if n == n_COLOR
  ylabel('Perceived Color Quality Scale');
else
  ylabel('Perceived Image Quality Scale');
end

% add title
if ill == 1
  if idx == idx1
    title('Paired Comparison Analysis for Nature Target Under Daylight');
  elseif idx == idx2
    title('Paired Comparison Analysis for Baby Target Under Daylight');
  elseif idx == idx3
    title('Paired Comparison Analysis for Fruit Target Under Daylight');
  elseif idx == idx4
    title('Paired Comparison Analysis for Paint Target Under Daylight');
  elseif idx == idx5
    title('Paired Comparison Analysis for CC Target Under Daylight');
  end
end

if ill == 2
  if idx == idx1
    title('Paired Comparison Analysis for Nature Target Under IncA');
  elseif idx == idx2
    title('Paired Comparison Analysis for Baby Target Under IncA');
  elseif idx == idx3
    title('Paired Comparison Analysis for Fruit Target Under IncA');
  elseif idx == idx4
    title('Paired Comparison Analysis for Paint Target Under IncA');
  elseif idx == idx5
    title('Paired Comparison Analysis for CC Target Under IncA');
  end
end

% conf_intervals - computes the confidence intervals for the results of the paired comparison analysis
% - Here, we are assuming Thurstone's Law of Comparative Judgement Case V
% Therefore, z-scores are our interval scale
% - Confidence intervals are calculated in terms of interval scale units
% inputs: obs - number of observers

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% interval_scale - interval scale output from paired_comparison function
%
% outputs: upper_int & lower_int - upper and lower confidence intervals
%
% functions called: none
%
% Written by Ellen A. Day 5/24/02
% last update EAD 5/30/02

function [upper_int,lower_int] = conf_intervals(obs,interval_scale)

% interval scale units
sigma = 1;
unit = sigma/(sqrt(2));

% standard error of scale values
std_error = unit/(sqrt(obs));

% for 95% confidence interval:
upper_int = interval_scale + 1.96*std_error;
lower_int = interval_scale - 1.96*std_error;

%**********************************************************************************************************************************************
% paired_comp_gof_tests - calculates Average Absolute Deviation and Mosteller's Goodness-of-Fit tests
%
% inputs:  S - some matrix from Ethan's code having to do with dealing with unanimous decisions
%          obs - number of observers
%          n - number of images
%          prop_matrix - proportion matrix from paired comparison
%
% outputs: interval scale = interval scale of the psychophysical experiment
%
% functions called: none
%
% Written by Ethan Montag
% last update EAD 6/11/02

function paired_comp_gof_tests(S,n,obs,prop_matrix)

% first get the scale differences and put them in a matrix
% use S

for i = 1:(n-1)
    for j = (i+1):n
        predicted_z(i,j) = S(i)-S(j);
        predicted_z(j,i) = S(j)-S(i);
    end
end

predicted_z;
predicted_prop = cdf('Normal',predicted_z,0,1);

% average absolute deviation absolute

for i = 2:n
    for j = 1:(i-1)
        countum(i,j) = abs(predicted_prop(i,j)-prop_matrix(i,j));
    end
end

aad = (2/(n*(n-1)))*sum(sum(countum))
if aad > .05
    disp('Bad fit via AAD!')
else
    disp('Good fit via AAD!')
end
% mosteller's chi-square from my notes
% NOTE: critical value must be much larger than chi-value for it
% to be a good fit - so it cannot be close otherwise it is a bad fit
% be careful using Mosteller's !!!

theta_real = asin(sqrt(prop_matrix)).*180/pi; % my notes
theta_predicted = asin(sqrt(predicted_prop)).*180/pi; % my notes

theta_real2 = asin(2*prop_matrix-1); % engeldrum
theta_predicted2 = asin(2*predicted_prop-1); % engeldrum

for i = 2:n
    for j = 1:(i-1)
        countum2(i,j) = (theta_real(i,j)-theta_predicted(i,j)).^2;
        countum3(i,j) = (theta_real2(i,j)-theta_predicted2(i,j)).^2;
    end
end

chi_val = sum(sum(countum2))/(821/obs); % my notes

chi_val2 = obs*sum(sum(countum3)); % engeldrum
dof = (n-1)*(n-2)/2 % degrees of freedom
critval = chi2inv(.95,dof)
if critval > chi_val
    disp('Good fit via Mosteller!')
else
    disp('Bad fit via Mosteller!')
end

%****************************************************************************
% Dual Scaling Analysis
%****************************************************************************

% ds_main - main function for dual scaling analysis
% inputs: none
% outputs: V - eigenvectors from dual scaling analysis
% k - diagonal matrix of largest eigenvalues
% flag - if flag == 0 then all the eigenvalues converged; otherwise not all converged.
% ii
% x - the stimuli configurations from dual scaling (optimal vectors)
% xadj - scaled values of x dimensions for plotting images
% y - the observers configurations from dual scaling (optimal vectors)
% yadj - scaled values of y dimensions for plotting observers
% delta - variance of the various dimensions (sqrt of eigenvalues)
% percenthomo - eigenvalues as percentages
% sumEVs - sum of eigenvalues
% rho - product-moment correlation (to indicate a linear relationship between two measurement variables- r=1 is best)
% plots comparing dimensions from dual scaling analysis
% functions called: compile_data_ds - loads data, illuminant is chosen, edited data is sent back out
% ds_obs_matrix - creates a matrix for each observer
% ds_full_matrix - creates a matrix from observer frequency (preference) matrices for use in dual scaling
% dual_scaling - does a dual scaling analysis on paired comparison data
%
% Written by Ellen A. Day on 10/13/02
% last update 10/16/02

% number of images for the 2 different experiment types
n_COLOR = 7;
n_IQ = 6;

% User chooses experiment type
n = input('Which experiment type? n color(1) n iq(2)?

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if n == 1 
  n = n_COLOR;
else
  n = n_IQ;
end

if n == n_COLOR
  % define the target indices
  idx1 = (1:21); % nature
  idx2 = (22:42); % baby
  idx3 = (43:63); % fruit
  idx4 = (64:84); % paint
  idx5 = (85:105); % CCDC
  idx6 = (106:126); % CC

  % User chooses target
  idx = input('Which target? \n nature(1) \n baby(2) \n fruit(3) \n paint(4) \n CCDC(5) \n CC(6)?\n');
  if idx == 1
    idx = idx1;
  elseif idx == 2
    idx = idx2;
  elseif idx == 3
    idx = idx3;
  elseif idx == 4
    idx = idx4;
  elseif idx == 5
    idx = idx5;
  elseif idx == 6
    idx = idx6;
  else
    idx = input('Which target? \n nature(1) \n baby(2) \n fruit(3) \n paint(4) \n CCDC(5) \n CC(6)?\n');
    if idx == 1
      idx = idx1;
    elseif idx == 2
      idx = idx2;
    elseif idx == 3
      idx = idx3;
    elseif idx == 4
      idx = idx4;
    elseif idx == 5
      idx = idx5;
    elseif idx == 6
      idx = idx6;
    else
      idx = input('Which target? \n nature(1) \n baby(2) \n fruit(3) \n paint(4) \n CCDC(5) \n CC(6)?\n');
      if idx == 1
        idx = idx1;
      elseif idx == 2
        idx = idx2;
      elseif idx == 3
        idx = idx3;
      elseif idx == 4
        idx = idx4;
      elseif idx == 5
        idx = idx5;
      elseif idx == 6
        idx = idx6;
      else
        idx = input('Which target? \n nature(1) \n baby(2) \n fruit(3) \n paint(4) \n CCDC(5) \n CC(6)?\n');
        if idx == 1
          idx = idx1;
        elseif idx == 2
          idx = idx2;
        elseif idx == 3
          idx = idx3;
        elseif idx == 4
          idx = idx4;
        elseif idx == 5
          idx = idx5;
        elseif idx == 6
          idx = idx6;
        else
          idx = input('Which target? \n nature(1) \n baby(2) \n fruit(3) \n paint(4) \n CCDC(5) \n CC(6)?\n');
            if idx == 1
              idx = idx1;
            elseif idx == 2
              idx = idx2;
            elseif idx == 3
              idx = idx3;
            elseif idx == 4
              idx = idx4;
            elseif idx == 5
              idx = idx5;
            elseif idx == 6
              idx = idx6;
            else
              idx = input('Which target? \n nature(1) \n baby(2) \n fruit(3) \n paint(4) \n CCDC(5) \n CC(6)?\n');
        end
      end
    end
  end
else
  % define the target indices
  idx1 = (127:141); % nature
  idx2 = (142:156); % baby
  idx3 = (157:171); % fruit
  idx4 = (172:186); % paint
  idx5 = (187:201); % CCDC
  idx6 = (202:216); % CC

  % User chooses target
  idx = input('Which target? \n nature(1) \n baby(2) \n fruit(3) \n paint(4) \n CCDC(5) \n CC(6)?\n');
  if idx == 1
    idx = idx1;
  elseif idx == 2
    idx = idx2;
  elseif idx == 3
    idx = idx3;
  elseif idx == 4
    idx = idx4;
  elseif idx == 5
    idx = idx5;
  elseif idx == 6
    idx = idx6;
  else
    idx = input('Which target? \n nature(1) \n baby(2) \n fruit(3) \n paint(4) \n CCDC(5) \n CC(6)?\n');
      if idx == 1
        idx = idx1;
      elseif idx == 2
        idx = idx2;
      elseif idx == 3
        idx = idx3;
      elseif idx == 4
        idx = idx4;
      elseif idx == 5
        idx = idx5;
      elseif idx == 6
        idx = idx6;
      else
        idx = input('Which target? \n nature(1) \n baby(2) \n fruit(3) \n paint(4) \n CCDC(5) \n CC(6)?\n');
          if idx == 1
            idx = idx1;
          elseif idx == 2
            idx = idx2;
          elseif idx == 3
            idx = idx3;
          elseif idx == 4
            idx = idx4;
          elseif idx == 5
            idx = idx5;
          elseif idx == 6
            idx = idx6;
          else
            idx = input('Which target? \n nature(1) \n baby(2) \n fruit(3) \n paint(4) \n CCDC(5) \n CC(6)?\n');
        end
      end
    end
  end
end

% load, compile, and edit data
[data,ill,obs] = compile_data_ds(idx);

% create a matrix with each observers frequency (preference) matrix
for i = 1:size(data,3)
freq_matrix(:,:,i) = ds_obs_matrix(data(:,:,i),n);
end

% create full matrix for dual scaling
[ds_matrix] = ds_full_matrix(freq_matrix,n,obs);

if idx == idx1
    num_tar = 1;
else if idx == idx2
    num_tar = 2;
else if idx == idx3
    num_tar = 3;
else if idx == idx4
    num_tar = 4;
else if idx == idx5
    num_tar = 5;
else
    num_tar = 6;
end
end
end

% perform dual scaling analyses
[image_type_xy,delta] = dual_scaling(ds_matrix,n,num_tar,ill);

% create scree plots for variance
scree_plot(delta,n,num_tar,ill);

%**********************************************************************************
% compile_data_ds - loads data, illuminant is chosen, edited data is sent back out
% inputs: idx - target indices
%          ill - illuminant
%          obs - number of observers for chosen illuminant
% functions called: load_data - loads data from observer files
%                    edit_data - all duplicates are taken out of data, then data is scaled
% Written by Ellen A. Day 9/13/02
% last update EAD 10/13/02

function [target,ill,obs] = compile_data_ds(idx);

% choose and load data
[data, dataA] = load_data;
obs_Daylight = 27;
obs_IncA = 27;
% data = input('Which data set do you want to use? \n all data(1) \n male(2) \n female(3) \n expert(4) \n naive(5)?
');
if data == 1
    [data, dataA] = load_data;
    obs_Daylight = 27;
    obs_IncA = 27;
else if data == 2
    [data, dataA] = load_data_male;
    obs_Daylight = 17;
    obs_IncA = 17;
else if data == 3
    [data, dataA] = load_data_female;
    obs_Daylight = 10;
    obs_IncA = 10;
else if data == 4
    [data, dataA] = load_data_expert;
    obs_Daylight = 19;
    obs_IncA = 20;
else data == 5
% [data, dataA] = load_data_naive;
% obs_Daylight = 8;
% obs_IncA = 7;
% end
% end
% end
% end

% edit data
for i = 1:size(data,3)
    temp(:,:,i) = edit_data(data(:,:,i));
end
data = temp;

for i = 1:size(dataA,3)
    temp2(:,:,i) = edit_data(dataA(:,:,i));
end
dataA = temp2;

clear temp;

ill = input('Which illuminant? 
Daylight(1) 
IncA(2)?
');
if ill == 1
    for i = 1:size(data,3)
        target(:,:,i) = [data(idx,:,i)];
    end
    obs = obs_Daylight;
else
    for i = 1:size(dataA,3)
        target(:,:,i) = [dataA(idx,:,i)];
    end
    obs = obs_IncA;
end

% put target data into 2D list
% target = permute(target,[1,3,2]);
% target = reshape(target,size(target,1)*size(target,2),size(target,3));

% ds_obs_matrix - creates a matrix for each observer
% inputs:  x - edited data matrix (num_pairs x 3 columns)
% n - number of images
% outputs: freq_matrix - frequency matrix for single observer
% functions called: none
% Written by Ellen A. Day on 10/16/02
% last update 10/16/02

function [freq_matrix] = ds_obs_matrix(x,n)

% number of image pairs
num_pairs = (n*(n-1))/2;

% separate columns
left_image = x(:,1);
right_image = x(:,2);

% 1 = left & 2 = right
choice = x(:,3);

% create a matrix that will hold the tally results
freq_matrix = zeros(n,n);

% frequency matrix
for i = 1:size(choice)
    if choice(i) == 1
        freq_matrix(right_image(i),left_image(i)) = freq_matrix(right_image(i),left_image(i)) + 1;
    end
end
else
    freq_matrix(left_image(i),right_image(i)) = freq_matrix(left_image(i),right_image(i)) + 1;
end

%*************************************************************************************************************************************************
% ds_full_matrix - creates a matrix from observer frequency (preference) matrices for use in dual scaling
% % inputs: freq_matrix - matrix of observer preferences
%     n - number of images
%     obs - number of observers
% % outputs: ds_matrix - matrix for use in dual scaling
% % functions called: none
% % Written by Ellen A. Day on 10/16/02
% last update 10/16/02
function [ds_matrix] = ds_full_matrix(freq_matrix,n,obs)

% number of image pairs
num_pairs = (n*(n-1))/2;

% define a matrix
ds_matrix = zeros(obs,num_pairs);
col = 0;
num_obs = 1;

for k = 1:obs
    for i = 1:n-1
        for j = i+1:n
            col = col+1;
            if freq_matrix(i,j,k) == 1
                ds_matrix(num_obs,col) = 1;
            else
                ds_matrix(num_obs,col) = -1;
            end
        end
    end
    num_obs = num_obs + 1;
    col = 0;
end

%*************************************************************************************************************************************************
% dual_scaling - does a dual scaling analysis on paired comparison data
% % - dual scaling script following chapter 6 of Nishisato
% % inputs: ds_matrix - matrix for use in dual scaling
%     n - number of images
%     num_tar - target number
%     ill - illuminant
% % outputs:
%     V - eigenvectors from dual scaling analysis
%     k - diagonal matrix of largest eigenvalues
%     flag - If flag == 0 then all the eigenvalues converged; otherwise not all converged.
%     ii - the stimuli configurations from dual scaling (optimal vectors)
%     xadj - scaled values of x dimensions for plotting images
%     y - the observers configurations from dual scaling (optimal vectors)
%     yadj - scaled values of y dimensions for plotting observers
%     delta - variance of the various dimensions (sqrt of eigenvalues)
%     percenthomo - eigenvalues as percentages
%     sumEVs - sum of eigenvalues
%     rho - product-moment correlation (to indicate a linear relationship between two measurement variables- r=1 is best)
% % functions called: none
%
function [image_type_xy,delta] = dual_scaling(ds_matrix,n,num_tar,ill)
F = ds_matrix;
if n == 7
    % rows: the number of stimuli for color accuracy experiment
    FColLabels=char('D1','pca6W','pca6','pinv6W','pinv6','TFpinv','RGB');
else
    % rows: the number of stimuli for image quality experiment
    FColLabels=char('pca6W','pca6','pinv6W','pinv6','TFpinv','RGB');
end
% columns: the number of subjects
FRowLabels=char('1','2','3','4','5','6','7','8','9','10','11','12','13','14','15','16','17','18','19','20','21','22','23','24','25','26','27');

%************Data above line********

% get # rows and columns of F matrix
[r,c]=size(F);

disp('Type 1 if the data is for a contingency table.')
disp('Type 2 if the data is for multiple choice data.')
disp('Type 3 if the data is in condensed multiple choice format.')
disp('Type 4 if the data is paired comparison format.')
disp('Type 5 if the data is for rank order.')
disp('Type 6 for successive categories: ')
datatype=input('------> '); 

if datatype == 1
    iters=min(r,c)-1;
end
if (datatype == 2) | (datatype == 3);
    noqs=input('Enter the total number of multiple choice questions: ');
    for nn=1:noqs
        disp(['Enter the number of choices for question ' num2str(nn)]);
        numchoices(nn)=input('------> ');
    end
if datatype == 3
    Ftemp=zeros(r,sum(numchoices));
    for ia=1:r
        temppos=1;
        for ib=1:c
            Ftemp(ia,temppos+(F(ia,ib))-1)=1;
            temppos=temppos+numchoices(ib);
        end
        %expand data
        if Ftemp(ia,:)
            % if expanded data
            origF=F;
            F=Ftemp;
        end
    end
end

[~,c]=size(F);
if iters==c-noqs;
    aveoptions=c/noqs; % average number of options
    v=aveoptions-1; % page 145 Nishisato
end

%*************** THIS IS THE PAIRED COMPARISON DUAL SCALING SECTION ***************
if datatype == 4
    RD=F;
    nstim=ceil(sqrt(2*c));
    A=zeros(c,nstim); % pairs x stimuli
    counter=1;
    for ip=1:(nstim-1)
        for jp=(ip+1):nstim
            A(counter,ip)=1;
            A(counter,jp)=-1;
            counter=counter+1;
        end
    end
    F=RD*A;
    [r,c]=size(F);
    iters=nstim-1;
    % F=(1/(nstim*(((nstim-1)/2))))*F'*F; %-(1/nstim)*ones(nstim,1)*ones(1,nstim);
    % F=F'*F;
    % [r,c]=size(F);
end
%*************** END OF PAIRED COMPARISON DUAL SCALING SECTION ***************

if datatype == 5
    % c is the number of stimuli
    F=c+1-2*F; % dominance table p 206 Nishisato
    iters=c-1;
    nstim=c;
end
if datatype ==6
    % expand to subjects-by-(category boundaries plus objects)
    % the # of columns is number of stim (n)
    tempF=F;
    F
    numcats=max(max(F)) % (Nishisato's m)input('Enter the total number of categories -> ');
    F=zeros(r,c+numcats-1);
    for si = 1: r % for each row (subject)
        previous=0;
        rank=0;
        kkup=0;
        for ci = 1 : numcats
            index=find(tempF(si,:)==ci);
            kk= size(index,2);
            if kk > 0
                rank=(kk+1)/2+kkup;
                kkup=kkup+kk+1;
                F(si,index+numcats-1)=rank;
                if ci < numcats
                    F(si,ci)=previous+kk+1;
                end
            end
        end
        previous=F(si,ci);
    end
    F=2.*F-(c+numcats);
    [r,c]=size(F);
    nstim=c;
    iters=c-1;
    F
% fr= the vector of row totals of F
fr=sum(F');
if datatype == 4 | datatype == 5 | datatype == 6 % try this soon
    fr=nstim*(nstim-1)*ones(size(fr));
end

% fc= the vector of column totals of F
fc=sum(F);  
if datatype == 4 | datatype == 5 | datatype == 6 % try this soon
    fc=r*(nstim-1)*ones(size(fc));
end

% Dr= diagonal matrix with row totals
Dr=diag(fr);

% Dc= diagonal matrix with column totals
Dc=diag(fc);

% ft=sum of all elements of F
ft=sum(sum(F));
if datatype == 4 | datatype == 5 | datatype == 6 % try this soon
    ft=r*nstim*(nstim-1);
    %ft=r*nstim;
end

B=Dr^(-1/2)*F*Dc^(-1/2);
B'*B;

(Dc^(-1/2)*ones(c,1)*ones(1,c)*Dc^(-1/2))/ft;
C1=B*B-(Dc^(-1/2)*ones(c,1)*ones(1,c)*Dc^(-1/2))/ft;
if datatype == 4 | datatype == 5 | datatype == 6 % try this soon
    %C1=(1/(r*nstim*(nstim-1)^2))*F'*F;
    %C1=sqrt(1/(r*nstim*(nstim-1)^2))*(F'*F);
    C1=C1-mean(mean(C1));
end

[V,k,flag] = eigs(C1,eye(size(C1)),size(C1,1)-1)% 100) % modified to compute all?
k=diag(k);
rho=sqrt(k);

ites=min(size(k,1),ites):
for j=1:ites

    %ii(j)=find(max(abs(V(:,j)))); % it has worked so far using this line but why?
    found=find((abs(V(:,j))==max(abs(V(:,j))));
    ii(j)=found(1);
    %i2=find(max(abs(V(:,2))))
    b(:,j)=V(:,j)/b(:,j); % mine

    %***********% try this from Dan Lawrence
    %b(:,j)=V(:,j);
    w(:,j)=sqrt(ft/(b(:,j)*b(:,j)))*b(:,j); % mine

    %***********% try this from Dan Lawrence
    w(:,j)=V(:,j)^sqrt(ft/(V(:,j)*V(:,j)))*sqrt(k(j)); %*sqrt(k(j)); %*sqrt(c-1);
%w1 = sqrt(ft/(b1^2*b1)) * b1
%w2 = sqrt(ft/(b2^2*b2)) * b2

x(:,j) = Dc(-1/2)*w(:,j);  %
% x1 = Dc(-1/2)*w1
% x2 = Dc(-1/2)*w2

xadj(:,j) = x(:,j) * sqrt(k(j));
% x1adj = x1 * sqrt(k(1))
% x2adj = x2 * sqrt(k(2))

y(:,j) = (1/sqrt(k(j))) * inv(Dr)*F*x(:,j);
% y1 = (1/sqrt(k(1))) * inv(Dr)*F*x1
% y2 = (1/sqrt(k(2))) * inv(Dr)*F*x2

yadj(:,j) = y(:,j) * sqrt(k(j));
% y1adj = y1 * sqrt(k(1))
% y2adj = y2 * sqrt(k(2))

delta(j) = 100*k(j)/trace(C1);
% delta1 = 100*k(1)/trace(C1)
% delta2 = 100*k(2)/trace(C1)

percenthomo(j) = 100*k(j);

end

if

if datatype == 2

for sol = 1:iters

rt = zeros(1, noqs);
placeholder = 1;
for nn = 1:noqs

    tempmat = F(:, placeholder:placeholder+numchoices(nn)-1);
    tempcol = zeros(r, 1);
    tempx = x(placeholder:placeholder+numchoices(nn)-1, sol);

    for ri = 1:r
        tempcol(ri) = tempx(find(tempmat(ri,:)));
    end

    TIS(:,nn) = tempcol;
    placeholder = placeholder + numchoices(nn);
end

SSTIS = sum(TIS(:,nn))*TIS(:,nn)';

end

for nn = 1:noqs

    sqrt(r^2(y(:,1)*y(:,1) - sum(y(:,1))^2));

    rt = r^2;
    etasquared = mean(rt.*rt);
    rsquared = etasquared/SSTIS';
    alpha = 1 - (1 - etasquared)/(noqs-1)*etasquared;

    % interitem correlation
    for ni = 1:noqs
        for nj = 1:noqs
            itemr(ni,nj) = (r^2*sum(TIS(:,ni).*TIS(:,nj))/sum(TIS(:,ni))*sum(TIS(:,nj)))/(sqrt(r^2*SSTIS(ni)) * sqrt(r^2*SSTIS(nj)));
        end
    end

    itemr;

end

end

end
eval('itemr num2str(sol) '= itemr;]);
eval('SSTIS num2str(sol) '= SSTIS;']);
eval('rsquared num2str(sol) '= rsquared;']);
eval('rt num2str(sol) '= rt;]);

end
end

end

end

x
xadj
y
yadj
delta
percenthomo;
sumEVs = trace(C1);
rho;

if datatype == 1

Order0=fr*fc/ft
previous=zeros(r,c);
Residual0=(F-Order0)

% **************
chisq0=sum(sum((Residual0.*^2)./Order0))
%chisq0=sum(sum(((F-Order0).*^2)./Order0)) % same thing
% **************
df0=(r-1)*(c-1)
critval0=chi2inv(0.95,df0)
disp(['Chi-square due to row-column association = ' num2str(chisq0)])
disp(['with ' num2str(df0) ' degrees of freedom'])

if critval0 < chisq0
disp(['significant at the 0.05 level.'])
else
disp([' NOT significant at the 0.05 level.'])
end

for j=1:(iters-1)
previous=previous+rho(j)*y(:,j)*x(:,j);
Order0=(1/ft)*Dr*(ones(r,1)*ones(1,c)+previous)*Dc;
eval(['Order num2str(j) '= Forder'])
eval(['Residual num2str(j) '= F - Order num2str(j)])
end

% I can't figure out what is going on in Nishisato's output and he doesn't explain
% dfprev=df0;
% for j=1:(iters-1)
% dfprev=dfprev-1-(r-j-1)-(c-j-1); %This is wrong for df but can be fixed easily
% eval(['chisq' num2str(j) '= sum(sum((Residual' num2str(j) '*^2)./Order' num2str(j) '))'])
% eval(['chisq' num2str(j) '= sum(sum(((F - Order' num2str(j) ')*^2)./Order' num2str(j) '))'])
% eval(['critical' num2str(j) '=chi2inv(0.95,dfprev)'])
% disp(['Chi-square due to row-column association = ' num2str(eval(['chisq' num2str(j)]))])
% disp(['with ' num2str(dfprev) ' degrees of freedom'])
% if eval(['critical' num2str(j)]) < eval(['chisq' num2str(j)])
% disp(['significant at the 0.05 level.'])
% else
% disp([' NOT significant at the 0.05 level.'])
% a little bit of plotting
% plotting column weights

figure

if dim2==0
    plot(0,xadj(:,dim1),'r*')
    for j=1:c
        text(0,xadj(j,dim1),[’ FColLabels(j,:)'])
    end
else
    plot(xadj(:,dim1),xadj(:,dim2),'r*')
    hold on
    plot(-1*yadj(:,dim1),-1*yadj(:,dim2),'go')
    for j=1:c
        text(xadj(j,dim1),xadj(j,dim2),[’ FColLabels(j,:)'])
    end
    for j=1:r
        text(-1*yadj(j,dim1),-1*yadj(j,dim2),[’ FRowLabels(j,:)'])
    end
end

xlabel(sprintf('Dim %d',dim1));
ylabel(sprintf('Dim %d',dim2));

image_type_xy = [xadj(:,dim1),xadj(:,dim2)];
close figure 1
close figure 2

% scree_plot - creates scree plots for dual scaling analysis
% inputs: none
% outputs:
% functions called:
% IMAGES: 1 - D1; 2 - pca6wRGB; 3 - pca6; 4 - pinv6wRGB; 5 - pinv6; 6 - tf_pinv; 7 - RGBpinv
% Written by Ellen A. Day 10/30/02
% last update EAD 10/30/02

function scree_plot(variance,n,num_tar,ill)

figure;
% plot bar graph of descending variance
bar(variance);
hold on;

v = variance;
if size(v,2) == 6
    v2 = [v(1), v(1)+v(2), v(1)+v(2)+v(3), v(1)+v(2)+v(3)+v(4), v(1)+v(2)+v(3)+v(4)+v(5), v(1)+v(2)+v(3)+v(4)+v(5)+v(6)];
    axis([0 7 0 100])
else
    v2 = [v(1), v(1)+v(2), v(1)+v(2)+v(3), v(1)+v(2)+v(3)+v(4), v(1)+v(2)+v(3)+v(4)+v(5)];
    axis([0 6 0 100])
end

plot(v2,'-*');
legend('Cumulative','Individual',-1);
xlabel('Dimensions');
ylabel('Percent Variance');
add_title_scree(n,num_tar,ill);

% add_title_scree - adds a title to dual scaling scree plots
% inputs:
% outputs: titles on scree plots
% functions called: none
% Written by Ellen A. Day 10/18/02
% last update 10/30/02

function add_title_scree(n,idx,ill)
if n == 7
    if ill == 1
        if idx == 1
            title('Scree Plot for Nature Target Under Daylight (Color Accuracy)');
        elseif idx == 2
            title('Scree Plot for Baby Target Under Daylight (Color Accuracy)');
        elseif idx == 3
            title('Scree Plot for Fruit Target Under Daylight (Color Accuracy)');
        elseif idx == 4
            title('Scree Plot for Paint Target Under Daylight (Color Accuracy)');
        end
    end
end
if ill == 2
    if idx == 1
        title('Scree Plot for Nature Target Under Daylight (Color Accuracy)');
    else if idx == 2
        title('Scree Plot for Baby Target Under Daylight (Color Accuracy)');
    else if idx == 3
        title('Scree Plot for Fruit Target Under Daylight (Color Accuracy)');
    else if idx == 4
        title('Scree Plot for Paint Target Under Daylight (Color Accuracy)');
    else if idx == 5
        title('Scree Plot for CCDC Target Under Daylight (Color Accuracy)');
    else
        title('Scree Plot for CC Target Under Daylight (Color Accuracy)');
    end
end
end
end
end

if n == 6
    if ill == 1
        if idx == 1
            title('Scree Plot for Nature Target Under Daylight (IQ)');
        else if idx == 2
            title('Scree Plot for Baby Target Under Daylight (IQ)');
        else if idx == 3
            title('Scree Plot for Fruit Target Under Daylight (IQ)');
        else if idx == 4
            title('Scree Plot for Paint Target Under Daylight (IQ)');
        else if idx == 5
            title('Scree Plot for CCDC Target Under Daylight (IQ)');
        else
            title('Scree Plot for CC Target Under Daylight (IQ)');
        end
    end
end
end
end

if ill == 2
    if idx == 1
        title('Scree Plot for Nature Target Under IncA (IQ)');
    else if idx == 2
        title('Scree Plot for Baby Target Under IncA (IQ)');
    else if idx == 3
        title('Scree Plot for Fruit Target Under IncA (IQ)');
    else if idx == 4
        title('Scree Plot for Paint Target Under IncA (IQ)');
    else if idx == 5
        title('Scree Plot for CCDC Target Under IncA (IQ)');
    else
        title('Scree Plot for CC Target Under IncA (IQ)');
    end
end
end
end
end
Color Difference Evaluation

% error_plots - this program creates plots that show the differences in CIEDE2000
% for the D1 image type minus all other image types

% D1 - image types in the following order for daylight:
% pc6W, pca6, pinv6W, pinv6, Tfpinv, RGB
cc_d = [1.0 1.1 0.7 1.1 1.6 0.2];
paint_d = [0.8 0.9 0.8 0.9 1.3 0.1];
gamblin_d = [1.2 1.6 1.2 1.6 2.0 0.7];
cc_d = [1.4 2.0 1.7 2.0 1.9 1.0];

% D1 - image types in the following order for incandescent A:
ccdc_a = [0.7 0.8 0.7 0.9 1.2 0.4];
paint_a = [0.3 0.3 0.4 0.3 0.6 -0.1];
gamblin_a = [0.8 0.9 0.8 1.0 0.9 0.5];
cc_a = [1.6 1.2 1.8 1.4 1.3 1.2];

% make plots
h1 = figure;
xaxis = 1:6;
hold on;
plot(ccdc_d,'r*-');
plot(paint_d,'g*-');
plot(gamblin_d,'b*-');
plot(cc_d,'m*-');
plot(ccdc_a,'r*:');
plot(paint_a,'g*:');
plot(gamblin_a,'b*:');
plot(cc_a,'m*:');
plot(cc_d+0.5,'r');

h2 = findobj(h1,'type','axes');
% image names
image_names = {'pc6W','pca6','pinv6W','pinv6','Tfpinv','RGB'};
% change the x tick labels to the image types
set(h2,'XTickMode','manual');
set(h2,'xtick',0:6);
set(h2,'xticklabel({'image_names{1}','image_names{2}','image_names{3}','image_names{4}','image_names{5}','image_names{6}'}));
set(h2,'FontSize',10);

% label axes
xlabel('Image Type');
ylabel('D1 minus Other Image Types');
title('Difference in CIEDE2000 Values from D1 CIEDE2000 Value');
legend('ccdc_d','paint_d','gamblin_d','cc_d','ccdc_a','paint_a','gamblin_a','cc_a','-1');

Schematics Analysis

% individuals - makes the grid chart that shows the pattern of individual results
% inputs: freq_matrix - frequency matrix for single observer
% outputs: grid chart that shows the pattern of individual results
% Note: Must use following line to move each image to where it is reachable:
set(gcf,'Position',[pos(1)-200 pos(2)-200 300 600]);
% functions called: none
% Written by Ethan Montag
% modified by Ellen A. Day
% last update 10/16/02

[data, dataA] = load_data;

% edit data
for i = 1:size(data,3)
    temp(:,:,i) = edit_data(data(:,:,i));
end
data = temp;

for i = 1:size(dataA,3)
    temp2(:,:,i) = edit_data(dataA(:,:,i));
end
dataA = temp2;

clear temp;
clear temp2;

% number of images for the 2 different experiment types
n_COLOR = 7;
n_IQ = 6;

% User chooses experiment type
n = input('Which experiment type? n color(1) n iq(2)?

if n == 1
    n = n_COLOR;
else
    n = n_IQ;
end

if n == n_COLOR
    % define the target indices
    idx(1,:) = (1:21);  % nature
    idx(2,:) = (22:42);  % baby
    idx(3,:) = (43:63);  % fruit
    idx(4,:) = (64:84);  % paint
    idx(5,:) = (85:105); % CCDC
    idx(6,:) = (106:126); % CC
else
    % define the target indices
    idx(1,:) = (127:141); % nature
    idx(2,:) = (142:156); % baby
    idx(3,:) = (157:171); % fruit
    idx(4,:) = (172:186); % paint
    idx(5,:) = (187:201); % CCDC
    idx(6,:) = (202:216); % CC
end

% which illuminant
ill = input('Which illuminant? n Daylight(1) n incA(2)?

if ill == 1
    data = data;
else
    data = dataA;
end

initials = '%1'; %2'; '%3'; '%4'; '%5'; '%6'; '%7'; '%8'; '%9'; '%10'; '%11'; '%12'; '%13'; '%14'; '%15'; '%16'; '%17'; '%18'; '%19'; '%20'; '%21'; '%22'; '%23'; '%24'; '%25'; '%26'; '%27';
[r,c] = size(initials);

% get frequency matrix for all 6 targets for each observer (result is a 7 x 7 x 6 x 27 matrix)
for q = 1:r
    for k = 1:6
        data_temp = data(idx(1,:),idx(6,end,:),q);
    end
end
if n == 6
    new_idx(1,:) = (1:15); % nature
    new_idx(2,:) = (16:30); % baby
    new_idx(3,:) = (31:45); % fruit
    new_idx(4,:) = (46:60); % paint
    new_idx(5,:) = (61:75); % CCDC
    new_idx(6,:) = (76:90); % CC
else
    new_idx = idx;
end
freq_matrix(:,:,k,q) = ds_obs_matrix(data_temp(new_idx(k,:),:),n);
end
end

% make box plots for individuals
for target = 1:6
    % add up number of times each observer chose each image
    for i=1:r
        temp = sum(freq_matrix(:,:,i),1);
        person(i,:) = temp(:,target);
    end
    image1sum=sum(person);

    % creates gray scale
    % There are seven images so the gray scale has seven values 0, 1/6, 2/6, 3/6, 4/6, ... 6/6
    if n == 7
        graylist=[0:1/6:1]'*[1 1 1];
    else
        graylist=[0:1/5:1]'*[1 1 1];
    end
    figure;
    colormap(graylist);
    for j=r:-1:1
        % text(-2,-j-.15,[num2str(j*(-1)+22) ' initials(j*(-1)+22,:))
        text(-1,-j-.15,[initials(j*(-1)+(r+1),:)
        if n == 7
            rr=j; %*(-1)+22;
            patch([0+rr.5 1+i.5 1+i.5 0+i.5],[0+rr.5 0+rr.5 1+rr.5 1+rr.5],person(j*(-1)+(r+1),i)+1)
            %person1(j*(-1)+22,i);
            %pause(.1)
            hold on
        end
    else
        for i=1:6 % seven images
            rr=j; %*(-1)+22;
            patch([0+i.5 1+i.5 1+i.5 0+i.5],[0+rr.5 0+rr.5 1+rr.5 1+rr.5],person(j*(-1)+(r+1),i)+1)
            %person1(j*(-1)+22,i);
            %pause(.1)
            hold on
        end
    end
    axis('equal')
    %axis([-2 6 -4 31])
    if n == 7
        axis([-2 8 -6 r+1]) % 8 is 7 images +1
    else
        axis([-2 7 -6 r+1])
    end
end
if ill == 1
    if target == 1
        title('Nature under Daylight')
    else if target == 2
        title('Baby under Daylight')
    else if target == 3
        title('Fruit under Daylight')
    else if target == 4
        title('Paint under Daylight')
    else if target == 5
        title('CCDC under Daylight')
    else
        title('CC under Daylight')
    end
end
else
    if target == 1
        title('Nature under Inc A')
    else if target == 2
        title('Baby under Inc A')
    else if target == 3
        title('Fruit under Inc A')
    else if target == 4
        title('Paint under Inc A')
    else if target == 5
        title('CCDC under Inc A')
    else
        title('CC under Inc A')
    end
end
end

if n == 7
    text(1,0,'D1','HorizontalAlignment','right','Rotation',90)
    text(2,0,'pca6W','HorizontalAlignment','right','Rotation',90)
    text(3,0,'pca6','HorizontalAlignment','right','Rotation',90)
    text(4,0,'pinv6W','HorizontalAlignment','right','Rotation',90)
    text(5,0,'pinv6','HorizontalAlignment','right','Rotation',90)
    text(6,0,'TFpinv','HorizontalAlignment','right','Rotation',90)
    text(7,0,'RGB','HorizontalAlignment','right','Rotation',90)
else
    text(1,0,'pca6W','HorizontalAlignment','right','Rotation',90)
    text(2,0,'pca6','HorizontalAlignment','right','Rotation',90)
    text(3,0,'pinv6W','HorizontalAlignment','right','Rotation',90)
    text(4,0,'pinv6','HorizontalAlignment','right','Rotation',90)
    text(5,0,'TFpinv','HorizontalAlignment','right','Rotation',90)
    text(6,0,'RGB','HorizontalAlignment','right','Rotation',90)
end

axis('off');
pos = get(gcf,'Position');
set(gcf,'Position',[pos(1) pos(2) 300 600]);
set(gca,'Position',[0 0 0.9 0.9]);
end

%*******************************************************************