PERCEPTION OF COLOR QUALITY FOR NATURAL IMAGES VIEWED, EDITED, AND PRINTED WITHIN THE CONTEXT OF A HOME DIGITAL COLOR IMAGING SYSTEM

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Dissertation submitted to the faculty of
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in

Industrial and Systems Engineering

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January 29, 1999
Blacksburg, Virginia

Keywords: human factors, image quality, color imaging, digital imaging, soft-copy hard-copy matching, central composite design

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SUMMARY

Within the home environment there exits a host of digital color imaging (DCI) system configurations. The combination of devices and software at the consumer's desktop with devices and services at a remote location (e.g., Print at Kodak), creates a complex interaction of device, contextual, and observer characteristics. The complexity of the system may result in a disparity between the consumer's expectations and the final product. In particular, the cathode-ray tube (CRT) display has the potential to influence consumers' perceptions of image quality and their subsequent image manipulation activities. Depending on the inherent color bias and apparent contrast of the CRT, extensive image manipulation may occur, significantly altering the digital values of the image. Output generated by Print at Kodak will reflect any image manipulation undertaken by the consumer. Unaware of the calibration of their display, consumers can be expected to measure Print at Kodak output against their memory of the CRT "original". If manipulation was extensive, what the consumer receives from Print at Kodak will appear quite different from the softcopy version and thus, may be deemed unacceptable.

This research was designed to address the softcopy-hardcopy matching issues that arise from the home DCI system configuration just described. To this effect, four primary objectives were formed. The first of these objectives was to outline the pertinent contextual, observer, and display related factors that contribute to the generation and perception of color within a home DCI system. The remaining objectives were to determine the influence of CRT color balance on; (i) perceived color quality for softcopy and hardcopy photographs, (ii) softcopy editing behavior, and (iii) print acceptance. To meet these objectives, two experiments were conducted.

A pilot study was designed to test and select a software interface that facilitated softcopy editing and minimized the amount of time required of participants. In addition, the pilot study was used as a test-bed for reference photographs and a subjective color quality rating technique that would be employed in the primary study.

The primary study examined how the CRT display influenced perceived color quality of photographs generated at two points in a DCI system; on-screen photographs (softcopy) and photographic quality prints (hardcopy). CRT gamma, color temperature, and excitation purity were manipulated using an orthogonal, blocked, central composite design. Twenty-two Eastman Kodak Company employees viewed 6 photographs under each of the 15 CRT conditions. A magnitude estimation procedure was used to solicit color quality ratings for each softcopy photograph. Participants then were given an opportunity to edit color balance, brightness, and contrast for each photograph. The edited photos were printed and rated once again for color quality and acceptability.

Results indicated that monitor calibration influenced perceived softcopy color quality, softcopy editing behavior, and subsequent perceived hardcopy color quality. Perception of softcopy color quality ratings was determined predominantly by the CRT gamma level. The effect of color temperature was secondary, while excitation purity produced negligible effects on perceived softcopy color quality. Participants responded to CRT color balance differences through their editing behavior. In some cases, edits were large enough to significantly and negatively impact perceived hardcopy color quality. Gamma in particular, was the most significant predictor of hardcopy color quality ratings and rejection rates.

Additional differences were observed between first- and third-party photographs. Though initially perceived as having a higher color quality, third-party photos were more heavily edited than their first-party counterparts. This resulted in lower overall hardcopy color quality ratings and increased rejection rates, relative to the first-party photographs. The data indicated that the disparity between first- and third-party photographs may be due to differing criteria. Third-party photos appear to have been judged almost exclusively on technical merit. Whereas, personal criteria may have had greater influence on the judgment of first-party photographs.

Results from this research may be applied to the development of monitor calibration tools, scene balancing algorithms, and software, for the purpose of accommodating consumer image manipulation behavior, in the context of the home DCI system presented herein.

This research was supported by Eastman Kodak Company, Rochester, New York.

ACKNOWLEDGEMENTS

I would like to thank the many individuals who supported my endeavors and instilled a sense of purpose and enthusiasm. First, my committee: My advisor, Dr. Robert Beaton, provided guidance, display expertise, and an orientation to the greater scheme of things that I am truly grateful for. Dr. Michael Miller is distinguished for his sincere interest in my development as a student and colleague. His extensive technical aptitude and ingenuity were invaluable. Paula Alessi is recognized for her outstanding mentoring, color science expertise, and encouragement. She gave me the perspective to ground myself in the real world. Dr. Walter Wierwille is acknowledged for his comprehensive experience and superlative standards. His expertise and opinions were highly regarded. Dr. Albert Prestrude is recognized for his enthusiasm for issues of human color vision. He brought a refreshing and esteemed perspective to the project.

Though this project may appear deceptively unassuming on paper, it was, in fact, an elaborate orchestration of unimaginable talent and vast resources. There are dozens of individuals at Kodak without whom this project would literally never have been completed. I would like to acknowledge a few of them here.

I am beholden to the expertise of Mike Dupin, Pat Cottone, Geoff Woolfe, and Ed Giorgianni. They taught me an enormous amount about color science, statistics, and CRT electronics, all the while inspiring in me a desire for more. I am grateful for the opportunity to have had a glimpse of what could be.

I am indebted to Cathy Daniels, Doug Christoffel, Jerry Wagner, and Cindy Pellow for their technical prowess. They gave me the skills to generate and manipulate photographs on a level I had never imagined. And they managed to make me believe it was all in fun. I also am indebted to Jim Herbert and Rick Chapman for their fervent journey into uncharted waters, their mastery of CRT electronics, and their ability to accomplish the impossible. I am grateful for their good-natured and determined spirit.

Dave Schond, Kenny Johnson, and Eric Trabold ran the gauntlet to generate the thousands of photographs required for data collection. I am eternally thankful for their succor, their obliging accommodation, and their affable demeanor. To Laurie Schaefer I owe an enormous debt of gratitude for her day-to-day support. She listened, provided levity, and had an ardor for new challenges that I relish.

Heartfelt appreciation is due the individuals who volunteered for a four-week study and stayed to the end, six month later. I am thankful for their interest in the project, their patience, and their engaging company. Simply put, I was graced with the best participants ever.

Finally, I would like to thank my family and friends for encouraging my efforts, aligning me with the proverbial light, providing balance, indulging my need for distraction, and awaking my sense of adventure. You made this ride worth the fare.

The real voyage of discovery consists not in seeking new landscapes but in having new eyes.

Marcel Proust

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OVERVIEW

Within the consumer imaging industry, the desire for image accessibility has not only led to technological advances, it has been redefined by them. George Eastman's innovation of the "*you push the button - we do the rest*" photographic system was born in part from the philosophy that photography should be accessible to all, rather than to those with the resources to manage a cumbersome wet-plate system (Collins, 1990). Similarly, Edwin Land's desire to solve a query posed by his three year old daughter - "*Why can't I see [the pictures] now?*" - led to the development of instant image accessibility, the Polaroid Land camera (Montgomery, 1988). Since Land's invention of instant photography, digital technology has entered the imaging domain, and with its arrival, accessibility has come to mean much more than viewing images immediately after capture.

The traditional imaging chain of a film camera, chemical processing, and hardcopy output is no longer the only option for the color imaging consumer. The three functions of a complete color imaging system - image capture, signal processing, and image formation (Giorgianni & Madden, 1997) - can now be served by digital imaging devices. A capture device is required to record the original scene information. What is deemed as an original by the user is task specific. Thus, cameras, scanners, and PhotoCD writers may all be considered capture devices. Second, signal processing must occur to transform input energy into a format compatible with the output device. For digital cameras, scanners, and PhotoCD writers, computers perform the signal processing activities; chemical processing serves this function for film cameras; and the VCR performs signal processing for video cameras. Finally, image formation is required to display the original information. Electronic displays, projectors, and printers are examples of image formation devices.

Digital Color Imaging (DCI)

The introduction of digital devices and computer networks, has provided the user with a broader definition of image accessibility. Though it still embodies the philosophy of photography for the masses, accessibility also may be applied to the goals of image sharing, image reproduction, and image archiving. These new domains arise from the fact that digital technology empowers users to bridge the spatial domain in two important ways. First, many aspects of imaging may be treated as non-fixed-location activities. Image reproduction can be conducted just as easily from one's own living room as it can from a professional film developing center. As a result, manufacturers of digital color imaging components no longer

restrict their target audience to the professional photographer or photographic center: They now market their products to home users. Second, digital imaging technology allows the initiation of imaging activities at one location and the commencement of such activities at another. Consequently, service providers have followed on the heels of device and software manufacturers by offering on-line access to photographic networks, archives, and printing. As an example, home-users now are able to request photographic quality reproductions from professional print service providers via the world wide web.

Complex DCI systems may consist of multiple independent devices linked locally at the user's desktop, remotely via the internet, or some combination thereof. Given the flexibility introduced by remote devices, there are a myriad of possible imaging systems that could be formed. Of particular interest is one implementation in the home environment:

> The consumer captures original scene information using a traditional 35mm film camera. The film is taken to a photofinisher who develops the photographs and writes them to PhotoCD. When the order is taken home by the consumer, the CD is loaded into the computer, where photos can be viewed and edited using image manipulation software. Software such as, Microsoft Picture-it, Adobe PhotoDeluxe, and Kodak Picture Easy, allow manipulation of color balance, brightness, and contrast levels. After satisfactory viewing and editing, the consumer sends an image to Print at Kodak, via the Internet, for a photographic quality reprint.

When the computer CRT is used as a preview device for the printer, as it is in the DCI system just described, consumers may expect the printed photos to match the appearance of the CRT images, especially if editing occurred.

However, the seemingly simple task of generating color hardcopy photographs that perceptually match what is seen on the CRT display of a home digital color imaging system presents a challenge. The DCI system is a complex interaction of contextual, technological, and observer characteristics. The nature of the imaging devices themselves determines how color stimuli are generated for visual display and will, therefore, influence what colors are presented to the user. Most consumers will be unaware of the fundamental differences between the CRT display at their desktop and the Print at Kodak printer. The print is a reflective medium requiring ambient illumination and cyan, magenta, yellow, and black dyes or inks to generate the perception of color on paper. The CRT is an emissive medium that produces the sensation of color through luminescent red, green, and blue phosphors. These technologies produce different sensations of brightness and saturation, as well as different color gamuts that are not likely to align perfectly.

Furthermore, the CRT itself may have an inherent color bias determined at the time of manufacture and/or induced by drift over time. This bias may cause inaccurate presentation of neutrals. When viewing photos on a biased monitor, consumers may be unaware that the color

balance observed is a function of the CRT and not actually present on the photograph. Thus, the user may be driven to manipulate the color balance, brightness, or contrast of the photograph until a pleasing image is achieved. However, any image manipulation will alter the digital values of the image, resulting in a true color shift that will be passed on to the printer.

Finally, the color presented on the display or print is not necessarily the color perceived by the observer. Ambient illumination, qualities of the immediate and surrounding visual environment, and the level of visual chromatic adaptation to ambient illumination and/or CRT luminance, are all factors that may influence how the user perceives color (Wyszecki, 1986; Burnham, Evans, & Newhall, 1957; Hunt, 1996; Fairchild, 1995; Breneman, 1977; Luo, Gao, & Scrivener, 1995). Each of these aspects must be given due consideration before perceptual color matches between softcopy and hardcopy may be attained.

Knowledge Requirements of Digital Color imaging System Users

Although the imaging systems of Eastman and Land required very little skill or knowledge from the user in order to capture and view images, modern digital color imaging systems require more sophistication of their users. In order for users to produce what is intended, they must be aware that alterations in and around the imaging system will impact the outcome of their imaging activities (e.g., on-screen color manipulation) and, ultimately, their satisfaction with the photographs. Second, users must know what actions are required to compensate for the system state and its impact on perceptual image quality. Thus, users will need an accurate conceptual model of the capabilities of individual DCI components and the manner in which these components interact. However, most home users of DCI systems will not be trained in color science, digital technology, or the assumptions made by software packages used for color imaging. Consequently, users will lack the knowledge required to generate imagery per their intentions. In Norman's (1988) terms, the Gulfs of Execution and Evaluation will be wide enough that the user will be forced to expend great effort to infer system state and predict whether his/her imaging intentions will be met. System naiveté may result in frustration and disillusionment with DCI systems.

The potential for user confusion and frustration poses an interesting dilemma for Print at Kodak whose task is to generate a perceptually accurate, high quality print of an image viewed and edited on a home DCI system. The difficulty arises from the fact that Print at Kodak has no information regarding the color balance of home DCI components or the context in which the images were viewed. Without this information it is difficult to produce prints that accurately represent CRT renderings. It is reasonable, therefore, to suspect that a certain percentage of the prints produced by Print at Kodak will be deemed unacceptable by users. Because home imaging users are unlikely to understand the complexities of their DCI systems, they can be

expected to hold Print at Kodak responsible for prints that poorly match the (memory of the) softcopy image. It then becomes the sole responsibility of Print at Kodak to generate high quality images despite the limitations imposed by the home DCI system.

Research Goal

Assuming a good quality photograph on the consumer side and a good printer calibration on the Print at Kodak side, simply passing the photograph through the home DCI system without image manipulation, no matter how bad it appears on-screen, will result in a good quality print. For a neutral balanced CRT with appealing contrast, the consumer may undertake few, if any, editing actions. When this is not the case, the color balance of the CRT has the potential to exert undue influence on users' perceptions of color quality, resulting in substantial image manipulation activities. Consequently, prints generated by Print at Kodak will have color shifts, introduced by the consumers themselves, that may negatively impact perceived color quality and ultimately, print acceptability.

This dissertation examines the influence of CRT color balance on subjective color quality for images generated at two points in a home DCI system; on-screen (softcopy) photographs and photographic quality prints (hardcopy). The following objectives are addressed by this research:

- Outline the pertinent contextual, observer, and display related factors that contribute to the generation and perception of natural image color within a home digital color imaging system.
- Determine the influence of CRT color balance on perceived color quality for softcopy and hardcopy images.
- Determine the influence of CRT color balance on on-screen color editing behavior.
- Determine the influence of CRT color balance on print acceptance.

BACKGROUND

The digital color imaging system represents a complex interaction of human, environment, and technology. The intricacies of the system dictate that any attempt to understand the influence of the system on the user must be carefully designed. Before engaging in a study of cross-media reproduction then, it is important to establish an understanding of the factors that have an influence on what the user will perceive. What follows is a presentation of the historical interest in color, of selected color appearance phenomena, and of a computer controlled cathode-ray tube (CRT) display system. A history is provided as a means for aligning current color appearance issues with those that precipitated interest in the area. Early interest in color appearance brought about an awareness of many instances where color was not perceived as one would expect. Of these color appearance phenomena, several are pertinent to the home imaging domain and are subsequently discussed. Since human color perception is influenced by the capabilities of the display device as well as perceptual factors, a presentation of the color generating characteristics of CRTs follows. From a discussion of these areas, one can identify the salient factors expected to determine cross-media color matching success for a home imaging application.

Sources of Color

Color has been the focus of scientific pursuit for centuries. Its presence can be traced to the ancient Greek era where philosophers of the time debated and theorized on the source of color (Khuehni, 1981, 1989, 1997). Historically, color has been ascribed to the visible light spectrum, intrinsic characteristics of objects, and perceptual properties of observers. Pythagoras and his followers deemed color to be a property of materials, located on the surface of objects. Democritis and Hartley asserted color to be a consequence of the interaction of various earth elements. They believed color was a mental occurrence triggered by an external stimulus. In the case of Plato and Empedocles, color appeared as a consequence of both object and ocular emissions. They hypothesized the eye contained an inner light or flame, that when combined with energy released from external elements, would form color sensations.

Theophrastus would later diverge from both object based and biological based orientations to uphold that color was a function of light itself. This school was revived in the early 17th century by Descartes and Kirchner. Descartes believed color to be a function of specific particle qualities, like speed and rotation, while Kirchner held color production arose through the play of light and shadows. It was Newton who would settle the debate over the physical principles

of light through his experiments with prisms. Newton's findings combined with the development of optical tools shifted the focus of scientific endeavor to the pursuit of the properties of light, the generation of color, and the mechanisms responsible for human color perception.

Suppositions regarding physiological mechanisms of human color perception were born out of experiments and observations of color perception capabilities. Two scenarios often were used to investigate how and why people perceived color in a particular way: color matching scenarios, and later color appearance scenarios. The matching scenario required an individual to adjust the composition of a light source until it produced a color stimulus that was perceptually equivalent to a reference stimulus. Appearance scenarios focused on what caused an observer to perceive a single stimulus differently under various conditions. Thus, matching was concerned with composition, and appearance with context. The use of matching and appearance scenarios has led to the development of modern color vision theories. For the early Trichromatic theorists, matching scenarios were fundamental in the development of their beliefs. Subsequent, Opponent-Process theorists applied knowledge from appearance scenarios to enhance and expand upon existing color vision theories.

Theories of Color Vision

Trichromatic Theory of Color Vision

When Thomas Young developed his Trichromatic Theory he departed significantly from his predecessors toward the beliefs of Newton (Lang, 1983). Color scientists of the eighteenth century believed that light rays were of three basic types: red, yellow, and blue. They further believed that color was associated with the rays themselves and not a human response to light energy. But Young took a different stance in the formulation of his theory. He agreed with Newton who asserted that ". . . the rays to speak properly are not coloured. In them there is something else than a certain power and disposition to stir up a sensation of this or that colour" (cited in Kaiser & Boynton, 1996, p. 14). Young elaborated on Newton's concepts by postulating there were three different receptor elements in the retina, which when activated by light, produced the perception of color. This view was reinforced at the end of the century by philosophers such as Kant, who viewed perceptual experiences to be more a function of the structure of the human sensory system than a function of the physical stimuli themselves.

Young's theory was expanded on by Hermann von Helmholtz and has become known as the Young-Helmholtz Theory (a.k.a., Component Theory). The primary assumption of the theory is that the human visual system is composed of three distinct cone receptors, each of which is sensitive to different regions of the visual light spectrum. These spectral sensitivities are often

associated with red, green, and blue, but more appropriately should be associated with the long, middle, and short spectral wavelengths. When light enters the eye each receptor reacts selectively to the stimulus, sends its information through the visual system along its own pathway, which is combined by the brain to produce the sensation of color and lightness (Burnham, Hanes, & Bartleson, 1963). The perceptual color gamut is determined by various comparative combinations of the three primary signals. Lightness is determined by summing the three receptor signals.

As physicists, Newton, Young, and von Helmholtz were interested primarily in the physical aspects (e.g., behavior and characteristics of visible light) of color perception. They were far less interested in the physiological (e.g., pigments and receptors) or psychological (e.g., cognitive factors) aspects of color perception. Consequently, the Trichromatic Theory was built around color-matching experiments rather than color-appearance phenomenon. The scientists' focus on color-matching capabilities of normal and abnormal observers resulted in certain deficits for the Trichromatic Theory. Namely, notable observations of color appearance, such as simultaneous contrast[1] or the production of white from yellow and blue, could not be explained by the Theory. Trichromatic theorists believed that a specific color perception was unique to a specific combination of spectral energy. Therefore, they could not account for the observation that multiple spectral combinations generated equivalent color perceptions (i.e., metamerism). In fact, von Helmholtz was disinterested in determining why those visual sensations occurred. Instead, he attributed them to human judgment, the influence of learning and experience (McCann, 1973).

Though discoveries in the late 1960s proved the existence of three distinct visual receptors, each sensitive to a different spectral wavelength, the Trichromatic Theory did not completely address the complexities of human color vision. It would take the efforts of Herring, Jameson, and Hurvich, who approached the issue from the standpoint of color-appearance phenomenon, to develop a more complete theory of color vision.

Opponent-Process Theory of Color Vision

Ewald Herring was credited with the formulation of the Opponent-Process Theory of color vision, which like the Trichromatic Theory was expanded on by later theorists, namely Jameson and Hurvich. Herring held the same beliefs of his predecessors, that color perception was a function of the visual system and not the physical stimulus. His theory was similarly

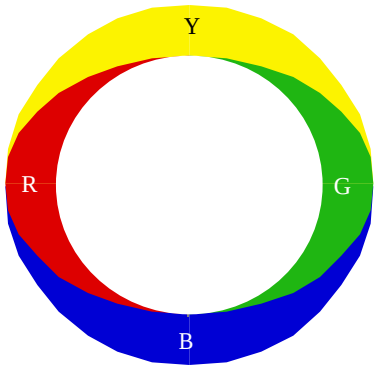
[1] Color appearance of a stimulus is often influenced by the area that directly surrounds it. For example, two identical patches of medium gray are presented to a normal observer. The first patch is surrounded by a medium green while the second patch is surrounded by a medium blue. The green surround will cause an observer to perceive the gray patch as having a slight red cast. The blue surround will cause the gray patch to appear slightly yellow. This phenomenon is known as simultaneous color contrast. It is also evidence of opponent-color processing. The surround color evokes a perception of gray that is in the direction of its opponent color: green evokes red and blue evokes yellow (Hurvich, 1981). See Figure 3 below.

predicated on the assumption that there are three types of receptors each containing a pigment sensitive to different spectral signals.

However, Herring's system differs from the Trichromatic Theory in that trichromacy is associated not with three spectral wavelengths but with three dimensions of visual color processing (i.e., opponent processes). His divergence stems from his observations that one never sees a reddish-green or a yellowish-blue. Herring consequently postulated that certain colors were mutually exclusive events that could not be seen simultaneously (Figure 1). As a result, information from the cone receptors was believed to be sent to one of three opponent response processes: light-dark, red-green, or yellow-blue. The post-receptor phase was characterized by the generation of opposing neural signals for each of the three response processes (Wyszecki & Stiles, 1982). A receptor detects a stimulus, passes the information on to the response process, which determines both the direction of the signal in terms of lightness, yellowness-blueness, or redness-greenness, and the degree of the signal. The perception of color and lightness is determined by the combination of responding process, direction of response, and magnitude of response. If all three opponent processes produce a signal at one directional extreme, the result will be the perception of warm colors such as red, yellow, and white. Signals at the other directional extreme will result in perception of cool colors such as green, blue, and black.

FIGURE 1: FOUR CRESCENT HUE CIRCLE

The various combinations of hue we are able to perceive are represented by overlapping primaries, from red-yellow clockwise through red-blue. Opponent hues never overlap because we never see red-greens or yellow-blues (or their inverses). Adapted from Hurvich (1981).



The appearance phenomenon that precipitated development of the Opponent-Process Theory continue to drive research efforts into human color vision. For example, observations of color constancy prompted Edwin Land to develop his Retinex Theory of color vision (Land, 1977). Land departed from his predecessors with the belief that the color of an object is never determined by simple observation of the object alone. Instead, it is determined through a comparative process of the object with its surround. Given that most perceptual situations do indeed involve complex stimuli viewed in relation to other visually intricate patterns, colors,

and / or textures, Land's departure was a reasonable one. In fact, color appearance research since Land has shown that not only does the viewing context influence what an observer perceives as color, but qualities of the stimulus itself, and the visual state of the observer also contribute to color perception. Due consideration to these factors is important because they are present in all image viewing situations and each is capable of significantly impacting an observer's overall impression of color appearance. The following sections present a detailed discussion of the factors deemed to be of particular interest for home DCI system environments. As a prelude to this discussion, a framework for the description of color will be introduced.

Color Appearance

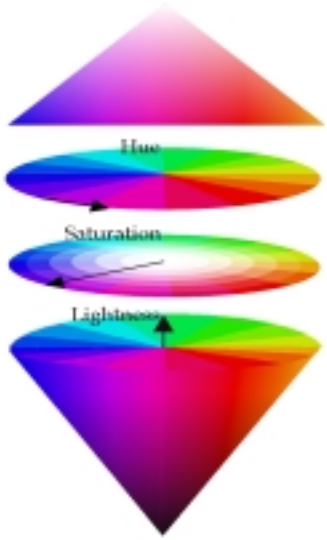
Color Attributes

Color appearance is generally described along three perceptual dimensions; hue, lightness, and saturation. The following represents the most recently agreed upon definitions of color attributes as presented by the American Society for Testing and Materials (1996). Figure 2 is a graphical representation of the three color dimensions defined.

- Hue: The attribute of color perception by means of which a color is judged to be red, orange, yellow, green, blue, purple, or intermediate between adjacent pairs of these, considered in a closed ring (red and purple being an adjacent pair).
- Saturation: Attribute of a visual sensation that permits a judgment to be made of the proportion of pure chromatic color in the total sensation.
- Lightness: The attribute by which a perceived color is judged to be equivalent to one of a series of grays ranging from black to white.

FIGURE 2: THREE DIMENSIONS OF COLOR

Color space may be described in terms of hue, saturation, and lightness. Color stimuli perceived to have equal hue lie on a vertical plane. Color stimuli perceived to have equal saturation lie on a cone. Color stimuli perceived to have equal lightness lie on a horizontal plane. Adapted from Wyszecki (1986).



Chromaticity Diagrams

All colors perceptible by an average human observer, under average daylight illumination, may be represented by a pair of coordinates in two-dimensional space. The two most commonly used diagrams were developed by the Commission Internationale de l'Eclairage (International Commission on Illumination or CIE): the 1931 2˚ chromaticity diagram and the 1976 uniform chromaticity scale (UCS) chromaticity diagram (CIE, 1986) (Figures 3 and 4). CIE chromaticity diagrams were designed only to indicate whether two colored stimuli match. They were not intended to describe the appearance of what is perceived, despite the presence of arbitrary color names and color boundaries. With this in mind, the diagrams are frequently used as a means of approximating the location and description of stimuli in color space. The 1931 diagram is defined by the chromaticity coordinates x, y (the abscissa and ordinate respectively), and Y (lightness) on an invisible third axis. The 1931 diagram affords the direct determination of color mixtures. A mixture representing half green and half blue will lie halfway between the green and blue points, on the line that connects the two points. However, equal distances on the diagram do not correspond to equal perceived color differences. For example, large changes in the green region must occur in order to be perceptible, while small changes in the red region elicit noticeable color shifts. In response to this issue, the 1976 UCS diagram was developed. It is defined by chromaticity coordinates u', v', and Y. Because the 1976 space is more perceptually uniform than the 1931 space, Euclidean distances between two coordinates (i.e., ΔE) will correlate more closely with just noticeable color differences for the human visual system.

The most striking feature of these diagrams are their horseshoe-shaped spectrum loci, formed by plotting the chromaticity coordinates of all wavelengths in the visible light spectrum. Any color represented by a point on the spectrum locus represents a pure hue, those within its boundary represent varying degrees of hue mixtures. As you progress toward the center of the diagram purity decreases, as evidenced by the large white region. Purity may be approximately correlated with the color attribute saturation (Hunt, 1991). Thus, colors that lie closer to the spectrum locus will appear more saturated than those at diagram center.

The third dimension of color appearance, lightness, is not depicted by the CIE diagrams. The charts represent two-dimensional mappings of hue and saturation at one level of lightness. They may be thought of as horizontal slices from three-dimensional forms. The forms are largest at their midsection, where lightness is moderate, and smaller at their crown and base

where lightness is high and low, respectively. The reduction in volume arises as a consequence of the inability to have full saturation at both high and low lightness levels.

FIGURE 3: 1931 CIE CHROMATICITY DIAGRAM

A graphical representation of Color space. CIE chromaticity coordinate x lies along the abscissa, y along the ordinate. Color names and boundaries are arbitrary and should not be used to infer perceptual experience.

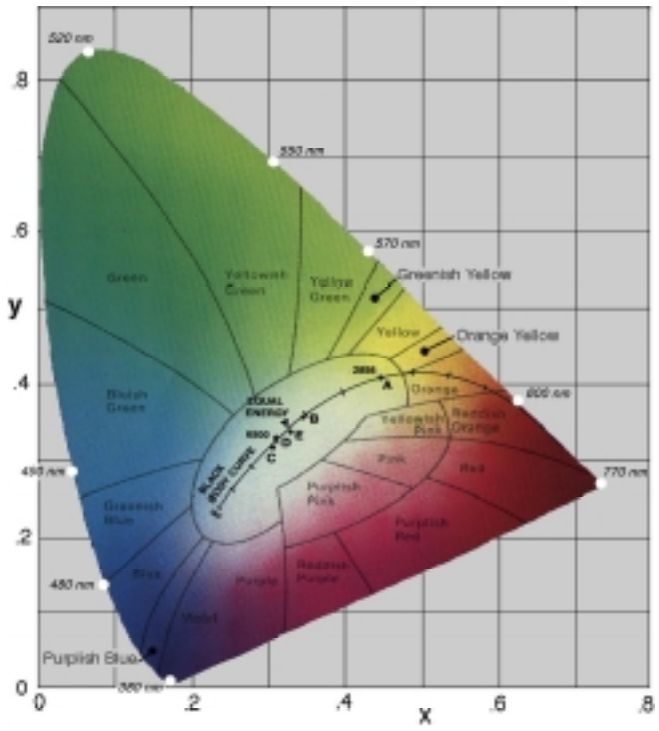


FIGURE 4: 1976 CIE UCS CHROMATICITY DIAGRAM

A graphical representation of Color space. CIE chromaticity coordinate u' lies along the abscissa, v' along the ordinate. Color names and boundaries are arbitrary and should not be used to infer perceptual experience.

In most naturally occurring perceptual situations, images are observed in close proximity to other colored stimuli rather than in isolation. What an observer perceives under these circumstances as color appearance depends on many factors. There are stimulus effects; such as size, complexity, and surface finish, contextual effects; like amount of illumination, type of ambient illumination, nature of background and surrounding areas, and observer effects regarding the eye's adaptation to a source of illumination. For home digital color imaging applications, contextual and observer effects are of particular interest. As such, they will be presented in more detail in the discussion that follows[2].

Illumination

The amount of ambient illumination will influence the color appearance and apparent contrast of images. Object colors will appear to become more colorful (i.e., exhibit more chromatic color) as the illumination level is increased (Wyszecki, 1986). Illumination increases also influence the brightness (i.e., intensity appearance) of object colors. Light colors such as white and light gray tend to decrease in brightness with increasing illumination. However, black and very dark grays tend to become slightly brighter to the observer, while mid-dark grays remain constant in brightness (Hunt, 1977b). The nature of the perceptual response to brightness changes under increasing illumination results in a reduced luminance contrast for a particular color set under observation. The range of white to black is decreased because of the perceived reduction in brightness for the whites and the perceived increase in brightness for the blacks.

In addition to the illuminance level, the type, or color, of an illuminant will influence the appearance of color images. As an example, an image seen under daylight will have a different color appearance than the same image viewed under either incandescent or fluorescent lighting. Warmer lighting will increase the perceived intensity of long wavelength colors while fluorescent lighting will cause a shift in perceived color toward the blue spectral range. In general, the appearance of a color will shift toward the color of the light source illuminating it (Burnham, Evans, & Newhall, 1957).

Brainard and Ishigami (1995) found that the type of ambient illumination has the same influence on the color appearance of CRT stimuli as it has on reflection media. The perceived color of the display shifts toward the color temperature of the light source. This phenomenon is caused by the dilution of light emitted by the CRT with that reflected from its faceplate. The interaction of reflection and emission not only shifts the perceived hue but also reduces the

[2] The subsequent color appearance discussion is limited to related colors only. Hunt (1977a) defines related colors as those in which "the luminances of the surroundings are sufficiently similar for them to appear, not as self-luminous, but as reflecting or transmitting objects, often having a gray content in their colour appearance...". Unrelated colors are those that have luminances significantly greater than their surroundings, appear to be self luminous, and do not appear to have any achromatic content.

perceived saturation (Tannas, 1992) and perceived luminance contrast (Hunt, 1996) of an image displayed on a CRT. These degradations become more pronounced as illumination level increases (i.e., as reflection off the faceplate increases).

Chromatic Adaptation

To a certain extent the human visual system counteracts the effects of color shifts induced by illumination sources. This process is known as chromatic adaptation. In many situations complete or nearly complete adaptation occurs allowing perceived colors to remain constant to the observer. Though chromatic adaptation is usually discussed with respect to illumination changes, it also is pertinent to consider in situations where chromaticity changes occur in self-luminous displays. For example, an individual who views images upon a CRT with a color bias, say in the blue direction, will partially adapt to this bias. This causes the whites produced by the CRT, which in fact have a blue tint, to appear more white than blue to the observer. The extent of the blue bias would only become apparent to the observer if the same image were presented under different conditions, such as in a print medium illuminated with an incandescent light source. At this point, the observer would perceive the CRT representation as more blue that the print representation.

Chromatic adaptation is influenced by several factors. First, like luminance adaptation, the chromatic adaptation process takes time. Fairchild and Reniff (1995) demonstrated that chromatic adaptation reaches full completion within 120 seconds of stimulus onset, with ninety percent adaptation occurring within 60 seconds. However, there are circumstances in which full adaptation is not reached.

Second, the presence of multiple light sources results in partial adaptation to both. Given a situation in which an observer views a CRT monitor under a given light source, the observer will adapt to a white point that lies somewhere in between that of the source and that of the display (Berns and Choh, 1995; Katoh, 1994).

Third, chromatic adaptation is governed by both sensory and cognitive mechanisms, and the latter do not automatically engage under all viewing conditions (Fairchild, 1988). When viewing prints in the presence of ambient illumination both cognitive and sensory mechanisms are active, resulting in virtually complete adaptation. Sensory mechanisms, the photoreceptors and neurons active in the early stages of visual processing, respond automatically to the energy of the illuminance source, allowing one to discount its effects on color appearance. Cognitive mechanisms engage when an observer has knowledge of scene content. This latter mechanism is evidenced by the fact that observers are able to see an object, such as a lemon, as having a consistent yellow color even under extreme lighting conditions that cannot be completely counteracted through sensory mechanisms.

Cognitive adaptation mechanisms may partially engage or may not engage at all under some viewing conditions. Generally, when observers view photographic prints they recognize specific objects in the photo and know from experience how those objects should appear. Consequently, the visual system adapts so that, no matter the lighting conditions at the time of viewing, the color of familiar objects appear as remembered. However, evidence suggests that softcopy representations of familiar objects are not interpreted as illuminated objects. Presentation of photographs on a CRT monitor alters the visual systems interpretation of the scene content. Items pictured in the photo are not interpreted as objects thus, the colors of those items are not treated as object colors. As a result, cognitive mechanisms are not fully engaged when viewing softcopy representations of photographs. This is evidenced by demonstrations that complete chromatic adaptation does not occur for softcopy imagery (Fairchild, 1993).

Surround

Viewing surround can be characterized by a description of the surface colors, materials, and finishes present in the viewing environment (e.g., walls and desktops). These factors, taken in consideration with ambient illumination, will determine the level of lighting present in the viewing environment. If an image is presented in a viewing environment different than the one it was created for, then surround effects will be present. Take as an example a situation in which one were to make a copy of a photograph on transparency film to be projected in a darkened room. Under these conditions, the projected image would not appear as pleasing as the photographic image. The dark surround in which the transparency image is projected, causes the image elements to appear lighter relative to the original image elements under constant surround. This means, in order to produce an optimal transparency reproduction the film image must have a higher contrast than the reflection print (Fairchild, 1995).

Appearance differences within the transparency film media itself also would be present in the photograph-to-overhead scenario. In such cases, the surrounding environment tends to be of a lower luminance than the elements within the transparent image during projection. This discrepancy in luminance causes the projected image to appear lighter than it would if viewed under luminance conditions equivalent to the projection source. But Hunt (1995) has found this lightening effect occurs inconsistently throughout the dynamic range of the picture. Dark areas are lightened to a greater extent than light areas of the picture, hence the surround lowers the apparent contrast of the image.

Surround also has been shown to influence the perceived saturation of images. Pitt and Winter (1974) and Fairchild (1995) both observed a significant reduction in saturation under dark surround conditions. However, Breneman (1977) counters this finding through his own

research in which dark surrounds required a mere 4% increase in saturation to match stimuli presented under light surround conditions. He contends the difference in observed results between studies can be attributed to stimulus complexity: where simple stimuli lead to larger saturation effects.

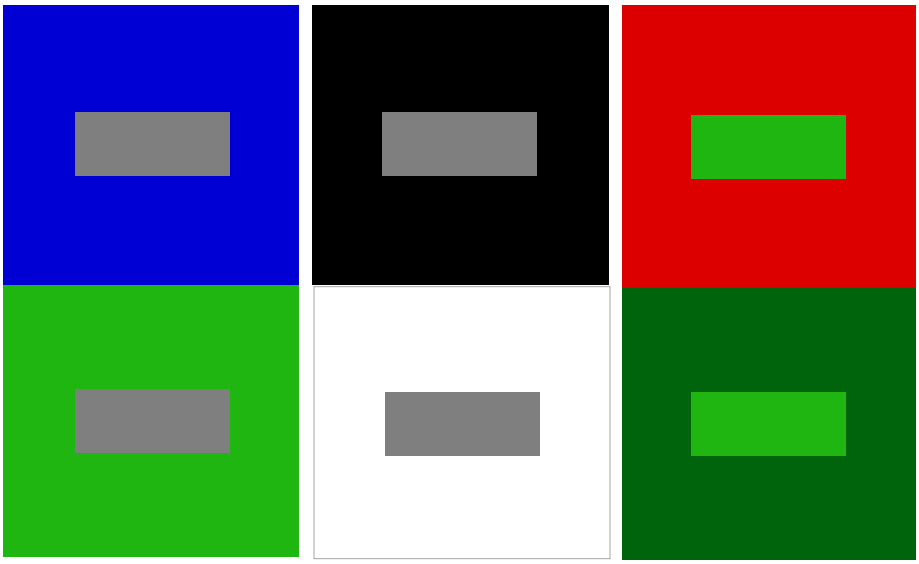
Background

Where surround effects are induced by a relatively broad field within the viewing environment, background effects are induced by the area that borders the field of focus. When external color sources abut an image (e.g., desktop patterns, photo mounting boards) the appearance of color within the image may be altered. Color shifts occur when the external source lies within a 10˚ (visual angle) radius of the target image. The background of an image, whether it be of chromatic or achromatic content, may influence the appearance of the target area (Figure 5).

Perceived lightness of an image can be altered by the lightness of the background. Dark backgrounds increase the apparent lightness of a target area while light backgrounds have the opposite effect (Hunt, 1995). Furthermore, Luo, Gao, and Scrivener (1995) reported that white backgrounds produced the greatest decrease in target lightness while black backgrounds produced the greatest increase in target lightness.

FIGURE 5: DEMONSTRATION OF BACKGROUND EFFECTS

(a) Background hue on color appearance is demonstrated. Though both gray strips are identical, the one amid green appears reddish, while the one amid blue appears yellowish. (b) Background lightness on lightness appearance is demonstrated. Again both gray bars are identical, but the gray amid black appears lighter. (c) Background hue on saturation appearance is demonstrated. Though both green strips are identical, the one amid red appears more saturated.



a b c

Perceived saturation has been found to be affected by both background hue and lightness. Luo et al (1995) reported light backgrounds reduced saturation, with whites producing the largest decrement. These authors researched hue influences on perceived saturation as well.

They found background hue reduced saturation when it was similar in hue to the target area. However, when the background and target area were composed of opponent hues the target color became more highly saturated. The opponent-hue effect also has been reported by Wyszecki (1986).

In addition, hue on hue influences were examined by Luo et al (1995), who found background hue influenced perceived target hue to a greater extent when the two areas shared common hues. Hue shifts were minimal when the two areas represented opposing hues. However, Ware and Cowan (1982) examined the influence of background hue on perceived target hue reporting an observed shift away from the background hue when the latter was one of the four primary colors (i.e., RGBY). Shift direction varied based on the hue of the test target, with target hue generally shifting toward the opponent hue of the background color. Hunt (1977b) has found the direction of perceived hue shift is dependent upon the size of the colored target. For larger targets (0.5˚ or more), color appearance shifts toward the opponent color of the background. For example, a target presented on a blue background would appear to shift toward yellow. Given a small target (less than 0.2˚), the target color shifts toward that of the background itself. Hence, a target on a blue background would shift toward blue.

The vast majority of color appearance phenomena research has been carried out on reflective media through measurement of surface colors. Though much of what has been learned regarding color appearance can be transferred to other media, such as the cathode-ray tube display, there are differences between the color generating capabilities of these systems.

Comparison of Softcopy and Hardcopy

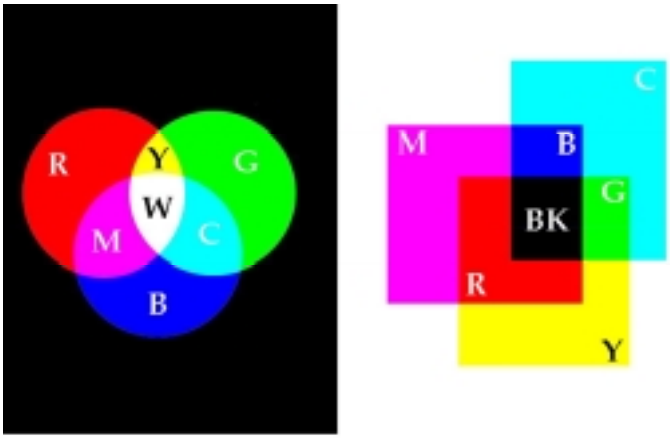
Print media generate a full color range through subtractive mixing of pigments or dyes having secondary hues (i.e., cyan, magenta, and yellow). An additive color system is employed by CRT displays, where the gamut of producible colors depends on the spectral energy of the phosphor primaries (i.e., red, green, and blue) (Figure 6). Additive systems rely on control of light output intensity and thus need no additional light sources in order for imagery to be perceived. Subtractive systems on the other hand, rely on control of light absorption and require a light source for image viewing. With respect to color generation, additive systems are generally able to produce greater saturation in the red, green, and blue primaries while subtractive systems achieve more saturation in the cyan, magenta, and yellow secondaries (McManus, 1989).

Many subtractive print media systems are capable of higher resolutions and higher maximum luminance levels (when the full range of ambient illumination is considered) relative to CRTs (Hunt, 1996). This is particularly true for high end devices such as those used by on-line

print service providers, but not for low end devices that are commonly found in consumer homes. The device with higher resolution, be it printer or monitor, will have a greater ability to produce fine detail, including gradual color shifts, while the device with higher maximum luminance will produce perceptually brighter colors. Home DCI environments are unlikely to include light sources that generate the full range of ambient illumination. Thus, in many situations, the CRT may be perceived as providing the brighter and more colorful image in relation to the print.

FIGURE 6: COLOR MIXING

In additive color mixing, what is perceived is the sum of the colors emitted by the display. White represents the presence of all primaries. In subtractive color mixing, what is perceived is the color reflected (i.e., not absorbed) by the medium. Here black represents the absorption of all light. Unlike additive systems, subtractive systems require ambient light for color to be perceived.



Additive Mixing *Subtractive Mixing*

Under strictly controlled experimental conditions it is possible to create an exact perceptual color match between softcopy and hardcopy media (P. J. Alessi, personal communication, September, 11, 1997). However, the home environment is far from that of the laboratory, meaning the goal then becomes one of producing a pleasingly close approximation between media. This goal can be realized if consideration is given to three primary areas of concern; the range of colors within each medium, the color temperature of the reference white associated with each medium, and the gamma value for each medium output system.

The range of colors producible by subtractive and additive systems is not necessarily the same. Understanding the color range differences between systems will aid in the task of harmoniously mapping colors from one system into the other. Of equal consideration is the intended viewing environment for hardcopy images and its similarity to the viewing environment of the display. Accurate color reproduction across media requires compensation for the differences between viewing environments. Finally, each device in the imaging chain translates input values to output luminances in a different manner. In most situations, the overall input-output relationship of the system must be adjusted to unity in order to achieve a

pleasing print from the imaging system. The influence of system gamma, color temperature, and color range on a CRT's color generating capabilities is presented below.

CRT Color Generation

CRT-Computer System Description

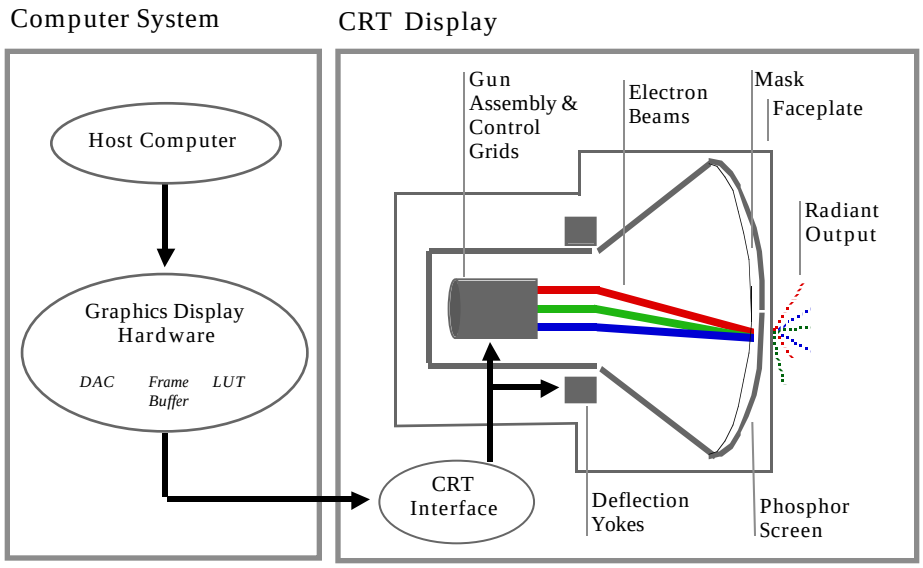
Image picture elements typically are represented within software and hardware by digital, red, green, and blue (RGB) code values. For a display system with a color depth of 8-bits per color channel, each channel can be assigned one of 256 code values: The range of code values extends from 0 for full off (i.e., black) to 255 for full on (i.e., white). For a tricolor CRT, the red, green, and blue channels may each be assigned one value between 0 and 255, for any one pixel. When each channel is assigned the same code value a neutral color will be attained. Any other combination of code values will yield a nonneutral hue. A particular visual pattern depends upon the original digital information generated by a computer software program. The accuracy with which it is rendered on the faceplate depends on characteristics of the graphics display hardware and CRT interface.

In order to be produced on-screen, code values must be transformed from digital to analog format. This transformation is linear and occurs in the graphics display hardware through use of a digital-to-analog converter (DAC) (Figure 7). The DAC generates analog voltages that are transmitted to the CRT interface. These voltages then are converted to electron beam drive currents through a power-law transfer function having an exponent commonly referred to as gamma (γ) (Berns, Motta, and Gorzynski, 1993).

Each CRT gun emits an electron beam toward the phosphor screen, that lies just inside the faceplate of the display. Control grids and deflection yokes are used to direct the flow of electron beams to a particular location. In most color CRTs, this process is aided through the addition of a perforated, metal mask located just inside the phosphor screen. The mask (e.g., circular aperture, slotted aperture, or aperture grill) is designed to align an electron beam with a particular phosphor dot on the screen. Bombardment from the electron beam causes the red, green, and blue phosphors to luminesce, emitting radiant energy at the faceplate of the display. The luminance a phosphor emits is proportional to the beam current, under normal operating conditions (Whitaker, 1994).

FIGURE 7: CRT-COMPUTER DISPLAY SYSTEM CONFIGURATION

Block diagram of a generic computer-controlled CRT display system. Adapted from Berns, Motta, and Gorzynski (1993).



Due to the nonlinear association between video voltage and electron beam current, luminance output from a CRT is nonlinear relative to the input values. The relationship of tricolor CRT-computer system electronics and luminance output may be represented by the following set of mathematical functions:

$$L_R = (\alpha_R I_R + \beta_R)^{\gamma_R} \quad (1)$$
$$L_G = (\alpha_G I_G + \beta_G)^{\gamma_G}$$
$$L_B = (\alpha_B I_B + \beta_B)^{\gamma_B}$$

Where L represents the luminance output, α the video amplifier gain, I the input voltage (or code value), β the video amplifier offset, and γ represents the numerical exponent that defines the shape of the curve relating video voltage to luminance (Berns, Motta, and Gorzynski, 1993). Video offset, gain, and gamma parameters significantly impact the light output response of a CRT monitor. Given that a CRT utilizes additive mixing of light from the three channels to produce color, offset, gain, and gamma parameters will influence both the luminance range and color range a display is capable of producing.

Color Gamut

A CRT's color output range is referred to as its color gamut. Though a CRT's gamma, gain, and offset parameters influence it's color gamut, the phosphors used to coat the CRT screen exert the greatest effect on color range. CRT phosphors consist mainly of metallic crystals that luminesce with a transfer of energy from electrons. The crystals selected at the time of manufacture determine the radiant energy given off by each phosphor primary (RGB) during excitation. Phosphor color can be measured directly using a colorimeter and is often plotted on

a 1931 CIE chromaticity diagram. The boundary formed by connecting the three primary phosphor chromaticity coordinates represents the range of color a display is capable of producing at a particular luminance level (Figure 8). Use of the CIE diagram allows one to visualize the range of color a display is capable of producing with respect to the range of color a person is capable of perceiving. Since the color range depicted by a boundary is specific to one luminance level, the full color gamut of the display is represented in three-dimensions by the boundary set generated from minimum to maximum luminance (Post and Lloyd, 1994). Figure 9 illustrates sample color ranges for a series of luminance levels. It can be seen that the color range for a CRT substantially changes shape, reduces in size, and approaches the neutral region with increasing luminance. When the display reaches its maximum luminance the color range will be limited to a single point in CIE color space. This indicates that a CRT at maximum, or near maximum, luminance level is unable to produce a large color range or highly saturated colors. The latter is indicated by the shift of the boundary away from the spectrum locus toward the white region of the CIE chromaticity diagram.

FIGURE 8: ISOLUMINANCE COLOR GAMUT

Graphical representation of a hypothetical set of CRT phosphor chromaticities and the color gamut they delineate. A color formed by any two-way combination of primaries will lie on the line connecting the primary chromaticities. Any color arising from a three-way combination of primaries will lie within the boundary. Adapted from Keller (1996).

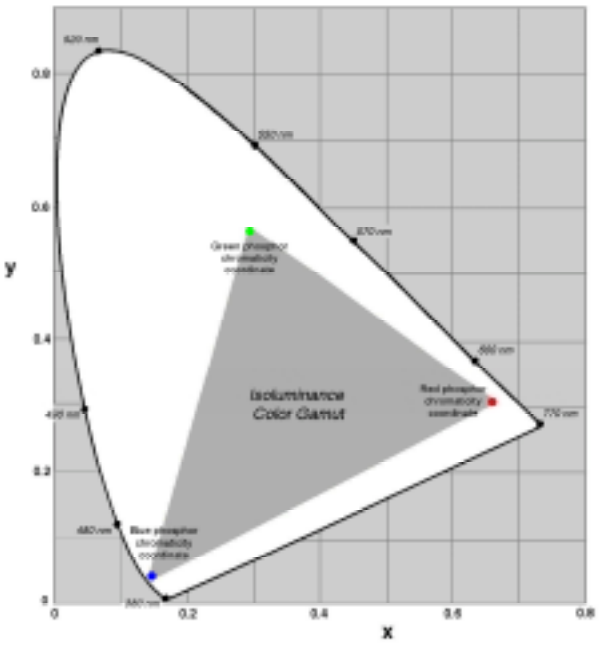
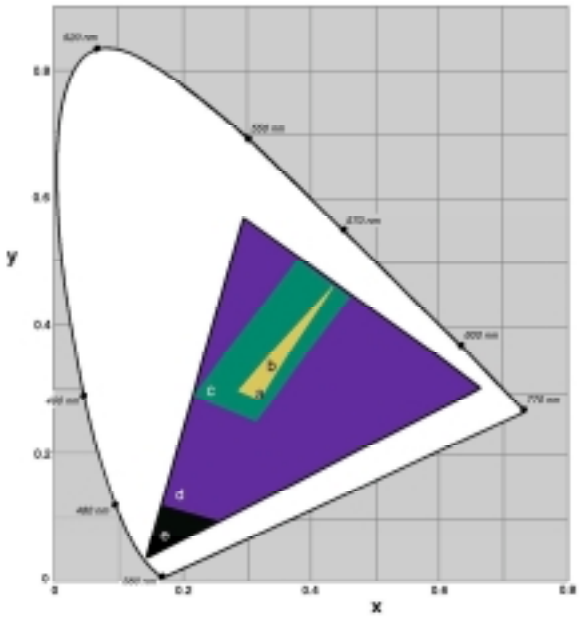


FIGURE 9:
MULTILUMINANCE COLOR GAMUT

A group of isoluminant color gamuts for a hypothetical CRT. The largest color range, represented in black (e), is produced at a luminance of 30 cd / m^2, purple (d) at 70 cd / m^2, green (c) at 230 cd / m^2, gold (b) at 270 cd / m^2, and white (a) at 300 cd / m^2. Color gamuts shrink about the neutral region with increasing luminance: culminating at a single value when the maximum luminance of the display is reached. Adapted from Post and Lloyd (1994) .



Video Nonlinearity

It can be seen in Figure 10 that a linear gamma results in a one-to-one mapping of input to output. That is, an input at half of maximum voltage yields a luminance output of half the maximum level. As gamma increases above one, the output becomes more skewed toward lower luminance levels (Figure 11). For a consumer CRT, the gamma value typically lies well above unity: Poynton (1993) cites values between 2.3 and 2.6 while others have found values between 1.0 and 3.0 (Cottone, 1996). The nonlinearity of the beam current-voltage relationship arises solely as a consequence of CRT gun electrostatics. Thus, CRT displays inherently respond nonlinearly to changes in video voltage levels and have gamma values greater than one. Furthermore, the monitor gamma value is determined by the manufacturer.

FIGURE 10: INFLUENCE OF GAMMA ON LUMINANCE OUTPUT

This chart depicts the outcome of gamma changes when video offset and gain are held constant at zero and 1.0, respectively (using Equation 1). As gamma values increase, the range between brightest and dimmest output remains constant, but the output becomes more skewed toward lower luminance levels.

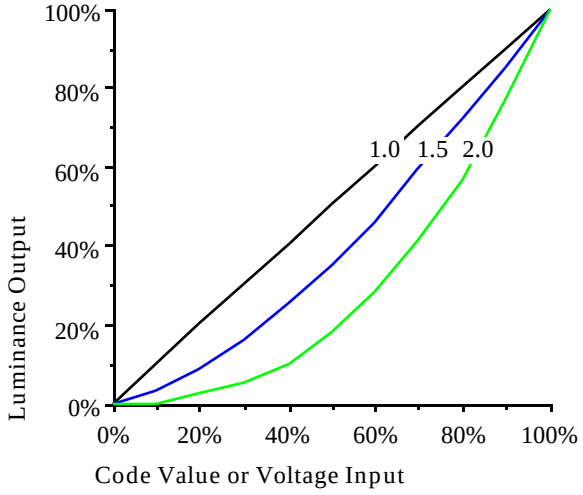
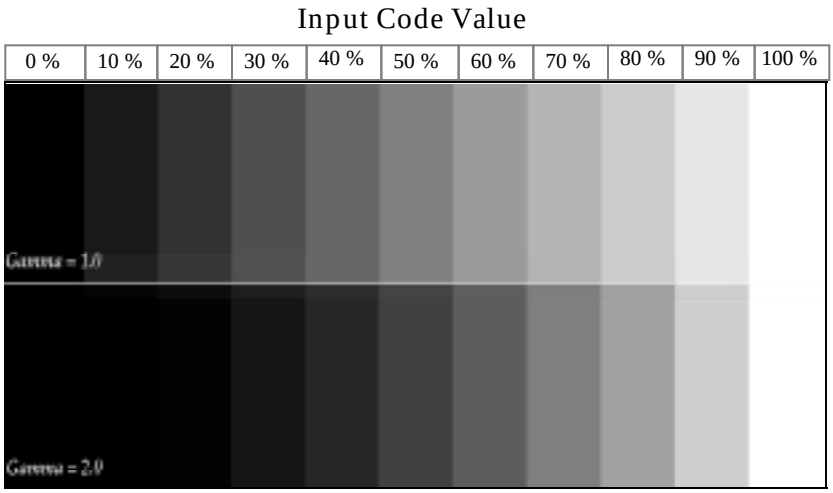


FIGURE 11: DEMONSTRATION OF GAMMA LEVELS

The top panel represents the neutral ramp for a system with a gamma value of 1.0. In this case the output is equal to the input code value (or voltage level). The lower panel demonstrates the disproportionate effect increased gamma has on the input-output relationship. At a gamma of 2.0, there is an emphasis on lower luminance output at the expense of upper luminance output.



Though the user is unable to select or adjust the display gamma, some software packages may be encoded to indirectly influence gamma levels in order to achieve a particular input-output relationship. This means image presentation on-screen does not necessarily reflect the monitor's gamma value. If gamma is adjusted in this manner, the change is affected through use of look-up tables (LUTs) that indirectly influence the luminance response by selectively altering input code values. Such adjustments are made in order to maintain the gamma of the imaging *system* at a particular level. Each device in the imaging chain (e.g., camera, scanner, monitor, printer) has its own gamma value. A necessary, condition for achieving an output image that matches the input image, is to maintain a *system* gamma of unity (Patterson, 1994). The process of altering system gamma to 1.0 (or any other value) is referred to as gamma correction.

Gamma correction may be carried out by anchoring the minimum and maximum output levels at the minimum and maximum input values. This method preserves the luminance range between brightest and dimmest output levels while altering the assignment of input-to-output in the midtone region. Maintenance of the luminance range means the contrast ratio of the display will remain constant. Yet midtone reassignment will result in changes to the apparent contrast of the on-screen imagery. As a result, an observer would be likely to describe an image as appearing more contrasty as system gamma is changed above 1.0. This is because gamma increases result in a darkening of mid tones relative to the minimum and maximum levels (Berger, 1997), and the human visual system is more sensitive to local luminance changes (within an image) than to global luminance changes (overall changes to an image) (Berns et al., 1993).

Alternatively, gamma correction could be accomplished by anchoring the extreme luminances at values toward the center of the code value scale, resulting in changes to all luminance levels. This method not only alters the brightness of the midtones in relation to the white and black points, but also reduces the contrast ratio of the display due to a reduction in the range from light to dark luminance.

Gamma settings influence the color appearance of imagery as well as apparent contrast. For example, in a linear system, a stimulus represented by 0% red, 40% green, and 80% blue, produces a blue-green ratio of 2:1, resulting in an output color near cyan (Figure 12). For a system with a gamma value of 2.5, the ratio of blue to green would be approximately 6:1, resulting in a hue shift toward blue accompanied by a reduction in brightness. In general, alterations to system gamma change the relative proportions of RGB input values to the extent that perceptible hue, brightness, and saturation shifts occur.

The method of gamma correction employed depends on how the software implementing the correction was written. Furthermore, gamma correction is usually transparent to the system user. That is to say, the user rarely receives the option of selecting a particular system gamma. If system gamma is altered at all, the determination is made and implemented by the software package run on the user's system. Since system gamma is generally not an option controlled by the user, the effects of gamma correction will be more noticeable between different systems than within a particular system.

FIGURE 12:
DEMONSTRATION OF GAMMA INDUCED COLOR CHANGE

Both patches are based on input values of 0% Red, 40% Green, and 80% Blue. The left patch simulates output from a system with a gamma of 1.0, the right a gamma of 2.5. The different system gamma values create two distinct color patches that vary in both hue and brightness.

Video Offset and Gain

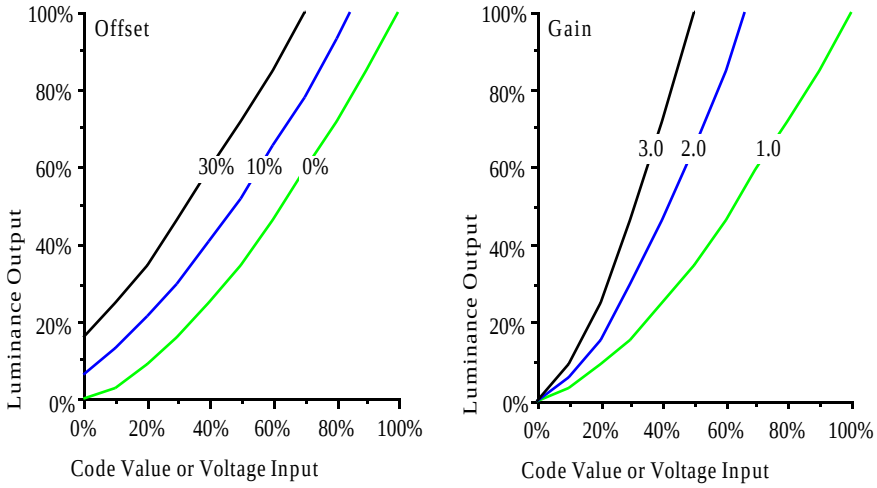
Video offset (β) refers to the output level assigned to the minimum voltage setting. Black is generated when minimum voltage input produces zero or near zero luminance. As offset increases, so to does the luminance output of the black point, moving the minimum output level further from a pure black toward that of gray. Raising the offset will result in changes to the

available luminance range and color capability of the display (Figure 13). First, the contrast ratio of the display will be reduced due to the raising of the minimum output level above black. Second, the inability to generate very low luminance outputs means deep, dark hues will not be attainable.

Where offset is more influential at lower luminance levels, gain exerts its influence mainly in the maximum luminance range. Video gain (α) refers to the ratio of voltage out to voltage in for a particular channel. Thus, adjusting gain for a channel either amplifies or diminishes the video signal (Figure 13). In certain cases, it may be desirable for one channel to be either over- or under-emphasized with respect to the others, depending on the calibration aim of the monitor. Given that the green channel is known to produce the highest luminance output, followed by the red and blue channels, respectively, changes in gain will influence the maximum luminance output a display is capable of producing. For example, when the green channel has an emphasized gain, maximum luminance will be greater than when either the red or blue channels are emphasized. Furthermore, the emphasis of one channel over the other will shift the gamut of producible colors toward the hue of emphasis.

FIGURE 13: INFLUENCE OF OFFSET AND GAIN ON LUMINANCE OUTPUT

These charts depict the outcome of gain and offset changes when gamma is fixed at 2.0 (using Equation 1). Increases in gain and offset reduce the number of steps between the brightest and dimmest output. In addition, increased offset reduces the output range by raising the luminance of black.



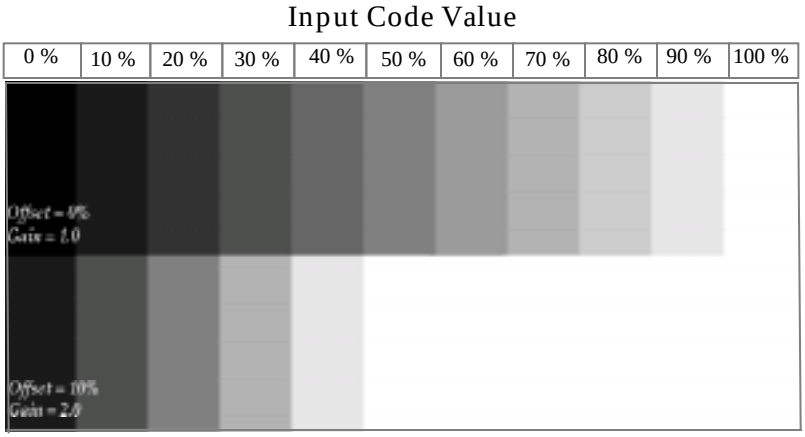
Some CRT monitor manufacturers provide users with monitor controls to directly adjust offset and gain parameters. These controls generally are configured to alter parameter levels simultaneously for all three channels, rather than offering individual control over a particular channel. With respect to offset, the control is usually, though not consistently, labeled "brightness". Díaz, Jiménez, Hita, and Jiménez del Barco (1996) demonstrated that increasing the brightness control resulted in a reduction to the range of colors the display could generate, both in terms of hue and saturation.

A second monitor control provided by manufacturers, often labeled “contrast”, adjusts the video gain level. Since the contrast control adjusts RGB gain by the same amount, it in effect amplifies / diminishes the video signal without altering the proportion of RGB contributed by each channel. Consequently, color balance of the display is maintained while the gain values are increased / decreased by some multiplicative factor. Since the color balance between the channels is preserved, the contrast control contributes mainly to the luminance level of the display. Thus, it’s impact will be limited to the brightness dimension of color appearance.

Taken together, increases in offset and gain are capable of significantly reducing the dynamic range of the CRT display by elevating the low luminance output levels. In addition, peak luminance levels are reached at lower code values. Given a gamma of 1.0, with offset and gain set to 0 % and 1.0 respectively, the standard one to one input-output relationship is achieved. Resetting offset to 10% combined with an increase in gain of 1.0 unit, yields both a reduction in dynamic range and a reduction in the number of input steps to maximum luminance (Figure 14). In the one-to-one input-output relationship, input values increasing in units of 10 produce output values increasing in units of 10. When the input-output relationship is altered equal input steps yield larger increments in output. Consequently, the combined effects of increased offset and gain result in fewer steps leading to maximum luminance and an increase in the size of the output for each input step.

FIGURE 14: DEMONSTRATION OF OFFSET AND GAIN INFLUENCES ON STEP SIZE

Two neutral ramps with a gamma value of 1.0. The top panel represents a one-to-one mapping of input to output, the bottom panel, a one-to-two mapping. Note that in the bottom panel a deep black is not achieved and larger output steps lead to maximum luminance at half maximum input.



As pointed out previously, gain adjustments to individual channels result in a change of color balance. A particular color balance is usually most perceptible when a reference white[3] stimulus is presented. Neutral balancing would result in the appearance of a pure white stimulus. Any other balance would require disproportionate emphasis of one or two channels and would result in a reference white biased in the direction of the emphasized gun(s). For this reason the ratio of the RGB gains is often used to adjust the color temperature of a display.

Color Temperature

Certain radiant bodies emit a specific spectral energy distribution when heated to a particular temperature. As temperature increases the color of emission progresses from dim red to bright white. The color emitted by these blackbody radiators can be described in terms of the temperature (degrees Kelvin) required to produce a certain radiant spectral energy, hence the term color temperature. Some common color temperatures include; candle flame at 1900K, tungsten incandescent lamps at 2900K, cool white fluorescent lamps at 4300K, and average daylight at 6500K (Vaughn, 1990). Color temperature is often plotted on a CIE chromaticity diagram along the blackbody curve (a.k.a., the Planckian locus) which lies in the neutral region (Figures 3, 4, and 15).

When the radiant energy of an emissive display produces a distribution similar to that of a blackbody radiator, it can be described as having a correlated color temperature. In the case of CRTs, correlated color temperature generally is associated with the reference white of the display. As a result, it is also known as the monitor white point. There exists a family of white point chromaticities that may be associated with a particular correlated color temperature. When represented in CIE chromaticity coordinates, the family of white points lie along an isotemperature line (Figure 15). Such lines cross the blackbody curve at their associated correlated color temperature chromaticity coordinate and extend both above and below the blackbody curve.

Like gamma, color temperature of a display is set during the product design stage and is determined by a combination of phosphor chromaticities, video gain level, and video offset level. Two white points are currently preferred among CRT manufacturers, 6500K and 9300K, with the latter being more popular in systems designed for graphical display applications (Brill and Derefeldt, 1991).

Whereas color temperature is a function of gain, offset, and phosphor chromaticity, and each of these parameters is known to affect a display's color gamut, it can be expected that

[3] The reference white is generated when all three electron guns are assigned the maximum code value (e.g., R=G=B=255). Ideally, the color temperature associated with the reference white should remain constant across all neutral levels generated by equal RGB code values. In practice, this does not always hold true, especially at lower code values where color temperature tends to diverge (Cottone, 1996).

changes in color temperature will alter a system's color generating capabilities. Furthermore, an observer will adapt partially to the color temperature of a display (i.e., chromatic adaptation), and may adopt the reference white as a true white against which relative lightness, saturation, and hue will be assessed. This means that judgments of color, or adjustments to color, made under one white point may not produce an equivalently acceptable image when rendered under a different white point. In fact, if the aim of color reproduction is to duplicate the qualities of the softcopy image then, the color temperature of the display must be the same as the color temperature of the illuminant used to view the reproduction (Brill and Derefeldt, 1991).

The preceding presentation of CRT characteristics produces an understanding of the many factors that are capable of influencing color generation for a computer-controlled imaging system. Other steps along the imaging chain (e.g., capture, scanning to PhotoCD, printing) offer additional complexities and challenges for color generation and perception. These issues, together with the influences of viewing environment, viewing context, and observer qualities, discussed previously, convey the complexity of color perception issues for a home digital color imaging system. Each of these factors is worthy of in-depth research but to study them all in one attempt would be futile. A more defined approach is called for; one that centers around a particular aspect of home DCI while respecting the remaining factors and their influences.

Purpose

Recall the specific home DCI system scenario previously described (page 11). For this situation, the user was expected to consider the CRT image the original, against which subsequent hardcopy output would be judged. It was assumed that a direct comparison between the softcopy photograph and the hardcopy print would not be made, mainly because of the time delay between submittal and receipt of Print at Kodak photographs. Rather the print would be compared to the user's memory of the original softcopy version. As such, the display system characteristics become of primary interest to designers of on-line print services. Consequently, this research effort focused on the electronic display and manipulation of color images within the context of a specific home digital color imaging system scenario.

The goal of this research was to determine whether users of home digital color imaging systems are influenced by the color balance of their CRT display. If they are, the influence may be expected to manifest itself in a variety of ways. First, perceived color quality of images viewed on-screen should be found to differ systematically with monitor calibration. Assuming the user is naive to the fact that what is viewed on-screen does not represent what would be generated by the printer, users could be expected to adjust images to reduce the undesirable effects induced by the monitor. Given the ability to compensate for a particular monitor

calibration, editing behavior also would be expected to differ systematically with monitor color balance. This in turn would result in prints that are biased toward the direction of the edits made on-screen. If a monitor were mildly biased, editing behavior may be minimal, and subsequent print bias may be so slight as to have a negligible effect on perceived color quality. However, at some point monitor setup should begin to negatively affect print quality, resulting in very low color quality and acceptance ratings. Therefore, the purpose of this study is fourfold:

- To determine whether system gamma, color temperature, and excitation purity have a significant effect on perceived softcopy color quality.
- To develop a model whereby editing behavior can be predicted from system gamma, color temperature, and excitation purity.
- To determine whether system gamma, color temperature, and excitation purity have a significant effect on perceived hardcopy color quality.
- To develop a model whereby hardcopy image acceptability can be predicted from system gamma, color temperature, and excitation purity.

PILOT STUDY

A pilot study was undertaken to answer several questions that would help guide the design of the primary study. It was known from previous research that image editing tasks require a significant time investment by participants. Thus, one goal of the pilot study was to select a software interface that facilitated editing and minimized the amount of time required of participants in the primary study.

The pilot study also was used as a test-bed for reference photographs that might be used in the primary study. The goal was to identify any photos that might elicit extreme editing behavior or be perceived as having extreme color quality. The candidate photographs were all selected, in part, based on their overall image quality. However, it would not be desirable to use photos that are perceived by the participants as having color quality that far exceeds or undercuts what they deem to be high color quality based on their own experience. Extreme photographs may bias their color quality ratings and subsequent color balancing decisions. Thus, the second goal of the pilot study was to determine which photographs would best serve as reference images for the primary study.

Finally, the pilot study was deemed an opportunity to pretest the magnitude estimation procedure. Of particular interest were; whether participants could effectively use an imagined reference photograph when estimating color quality, and whether the modulus value selected allowed an adequate range of quality levels.

Methods

Participants

Six individuals from Eastman Kodak Company, Human Factors Laboratory, in Rochester, NY, served as participants for this study. All were female between the ages of 17 and 50. Five had significant experience judging image quality, though not with respect to color.

Apparatus

Images: Six images were selected from three sources; the Kodak website, Kodak PhotoCD samplers, and the Kodak Creative Image Center Database. Two images were selected to fill each of three categories: scenes containing memory colors of blue sky and green grass, scenes containing memory colors of skintones, and scenes containing predominantly neutral tones (Appendix A).

All images were written to PhotoCD and then digitally altered through a series of image processing steps enabling them to be rendered in softcopy (Appendix B). Images were transformed from a YCC metric in PhotoCD format to a nonlinear monitor RGB metric in a noninterleaved, band sequential format. Image transformations were accomplished using Kodak internal software.

Display System: Images were presented on a Sony 17seII CRT display coupled with a PowerMac 8100/100av. Table 1 lists the characteristics of each monitor calibration used herein. The first setting, 4061K-green, represented a point on the 4061K isotemperature line, a distance of 15 ΔE^*_{uv} above the blackbody curve. The center position represented a point directly on the blackbody curve at 9300K (i.e., a ΔE^*_{uv} of 0). The third setting represented a point 15 ΔE^*_{uv} below the blackbody curve on the 14539K isotemperature line. Thus, these settings differed not only in terms of their color temperature but also in terms of their excitation purity.

TABLE 1: PILOT STUDY MONITOR CALIBRATION DATA

	Chromaticity Coordinates		**Gamma**		**Maximum Luminance**	
	Aim	Actual	Aim	Actual	Aim	Actual
4061K-green	0.3838x, 0.3982y	0.3730x, 0.3925y	2.0	2.038	100 cd/m^2	96.27 cd/m^2
9300 K	0.2849x, 0.2932y	0.2835x, 0.2913y	2.0	1.986	100 cd/m^2	99.49 cd/m^2
14539 K-magenta	0.2722x, 0.2591y	0.2694x, 0.2609y	2.0	2.042	100 cd/m^2	97.64 cd/m^2

The monitor settings were achieved through physical manipulation of monitor hardware. Internal CRT gain and offset controls were digitally altered to achieve a particular monitor calibration. Sony Digital Alignment Software (DAS) was used to communicate with the monitor gain and offset controls to achieve the desired chromaticity. Real-time measurements of monitor color balance were taken during calibration, using an LMT C2200 colorimeter. When the aim chromaticity coordinates and gamma level were achieved the gain and offset values were saved to a file which was later downloaded directly into a monitor memory location. The Sony display was capable of holding and recalling three distinct monitor calibrations, accessible via the monitor front panel controls. After calibration, each setting was verified for agreement with the aim values using a PhotoResearch PR703 spectroradiometer.

Editing Software: A software color tool was developed in-house that would allow participants to adjust color, brightness, and contrast of on-screen images. Internal development was desired so that it was known exactly how the images were changing in response to color,

brightness, and contrast edits (Appendix C). Internal development also allowed inclusion of data collection features that recorded both ratings and edit behavior.

The rating screens displayed a 4" by 6" photograph at screen center against a 20% gray background. All photographs were presented with a small white border in order to facilitate cognitive adaptation effects. Editing screens displayed the photographs centered against a 20% gray background, surrounded by a white border, and accompanied by a set of editing tools. Editing occurred in RGB Color space using one of two user interface scenarios: sliders or a modified ring-around (Appendix C). Each interface allowed the user to individually adjust red balance, green balance, blue balance, brightness level, and / or contrast level of a photograph. Adjustments were uniformly applied to the whole photograph. The color tool did not allow definition and adjustment of areas within a photograph. It should be noted that this tool applied the edit values to the original image data after each edit was made, rather than applying edit values to the edited image. Therefore, a user could truly undo an edit without loss of image data due to clipping.

Procedure

Participants were asked to provide a personal definition of color quality followed by a written description of a high color quality photograph they were familiar with (Appendix D). This image was supposed to meet all color quality requirements identified in their definition. The imagined reference photograph was assigned a modulus of 200. All experimental photographs were given a color quality rating proportional to the modulus, using a magnitude estimation technique.

After a color quality rating was supplied, participants were given an opportunity to edit the color balance of each photograph to their liking. Upon completion of editing, a second rating screen was displayed to solicit post-edit color quality ratings.

At the presentation of each new monitor calibration, participants were asked to view the displayed photograph for 1 minute before proceeding. This was done to accommodate the chromatic adaptation mechanisms of the visual system.

Ambient surround was designed to simulate typical home computer viewing environments (Cottone & Miller, 1996). Wall and tabletop surfaces were covered with a 20% gray material. The room was illuminated by two incandescent (tungsten) lamps. Absolute illuminance level at the desktop, between the participant and the display, was measured at 20 lux, using a Minolta illuminance meter. Color temperature and CIE chromaticity coordinates for the light sources were measured from a halon chip using a PhotoResearch PR703 spectroradiometer. The results were 2592 K and (0.4687x, 0.4124y) respectively.

Design

A full factorial (6x3x2), within-subjects design was employed for three independent variables: scene, monitor calibration, and color tool interface (Table 2). Participants viewed all scenes twice for each monitor calibration, once with the slider interface and once with the ring-around interface. Presentation of monitor calibrations was completely counterbalanced. Within a monitor setting the remaining treatment combinations were randomized.

TABLE 2: PILOT STUDY INDEPENDENT VARIABLES AND LEVELS

Levels	Scene	Monitor Calibration	ColorTool Interface
one	barn	4061 K-green	slider
two	boy	9300 K	modified ring-around
three	dog	14539 K-magenta	-
four	snow	-	-
five	stones	-	-
six	trio	-	-

Results

Dependent Measures

Eight dependent measures were recorded: pre- and post-edit ratings, red, green, blue, brightness, and contrast edits, and the length of time taken to edit a photograph. Ratings fell between 50 and 400. Edit magnitudes ranged from -42 to 80, with positive numbers denoting increases and negative numbers denoting decreases. The range for time ran from 6 seconds to just over 6 minutes.

Three main analyses were conducted on the dependent variables. Of particular interest were: (i) whether editing time varied by color tool interface, (ii) whether pre- and post-edit ratings varied by monitor and/or scene, and (iii) whether any of the five editing dimensions varied by monitor, scene, and/or GUI. Unless indicated otherwise, all hypothesis tests were conducted using an alpha level of 0.05. Likewise, all post hoc tests controlled familywise error rates at an alpha level of 0.05. Minitab (v10.5 extra for Macintosh) statistical software was used to run all analyses.

Editing Time

An Analysis of Variance (ANOVA) was conducted for editing time (in minutes) across all three independent variables. Significant differences were found for the color tool interface alone. Faster editing times were associated with the modified ring-around interface. Editing time with the slider interface was approximately 1.5 times longer than that of the modified ring-

around interface. Tables 3 and 4 present the ANOVA summary and mean edit times, respectively.

TABLE 3: PILOT STUDY ANOVA SUMMARY TABLE FOR EDITING TIME

Source	DF	SS	MS	F	P
Monitor	2	0.3646	0.1823	0.23	0.796
GUI	1	6.9771	6.9771	8.72	0.004
Scene	5	0.9551	0.1910	0.24	0.945
Monitor*GUI	2	0.7426	0.3713	0.46	0.629
Monitor*Scene	10	7.2419	0.7242	0.91	0.529
GUI*Scene	5	3.5781	0.7156	0.89	0.486
Monitor*GUI*Scene	10	4.8165	0.4816	0.60	0.811
Error	180	143.9587	0.7998		
Total	215	168.6344			

TABLE 4: PILOT STUDY MAIN EFFECTS OF INTERFACE, MONITOR CALIBRATION, AND SCENE ON EDITING TIME

	Interface		Monitor Calibration			Scene					
	Sliders	Ring-around	4061-grn	9300	14539-mag	barn	boy	dog	snow	stones	trio
Mean	1.24	0.88	1.11	1.01	1.06	1.16	0.98	1.02	1.12	1.09	1.00
SE	0.10	0.06	0.10	0.11	0.10	0.15	0.19	0.13	0.18	0.11	0.12
N	108	108	72	72	72	36	36	36	36	36	36

Pre-Edit and Post-Edit Ratings

The use of an imagined photograph as a reference for the magnitude estimation procedure was in essence a free modulus procedure, despite the fact that each reference was assigned a fixed modulus value of 200. Thus, participants' reference photographs represented a variety of quality levels. In addition, each individual scaled color quality differently producing varying ranges between the highest and lowest color quality ratings solicited. To adjust for these two sources of inter-participant variability for color quality responses, a transformation was made to all ratings obtained via magnitude estimation. The data transformation was a modification of the procedure described by Engen (1971) and involved the following steps.

1. The logarithm (base 10) was taken of each participant's rating at each treatment.
2. The geometric mean rating for each participant was calculated by taking the arithmetic average of the Log_{10} values obtained in step 1. One geometric mean was generated for each participant by collapsing across all treatment conditions.
3. A grand geometric mean was calculated by taking the arithmetic average of the Log_{10} values obtained in step 2. One geometric mean was generated by collapsing across all participants.
4. The grand geometric mean was subtracted from each participant's geometric mean (i.e., the step 3 value was subtracted from each value obtained in step 2).

5. The values obtained in step 4 were then subtracted from the values obtained in step 1. For example, the difference between the grand geometric mean and participant 7's geometric mean was in turn subtracted from every Log_{10} value obtained for participant 7 in step 1.
6. The antilog was taken for the values obtained in step 5.

A multivariate analysis of variance (MANOVA) was run on the transformed pre-edit and post-edit ratings over the full factorial design. Results revealed significant differences were present among the monitor levels (Wilk's $F_{4,358} = 3.19$, $p = 0.014$) and the scene levels (Wilk's $F_{10,358} = 6.26$, $p = 0.000$). No significant differences were present for interface (Wilk's $F_{2,179} = 0.619$, $p = 0.539$).

A subsequent univariate ANOVA was run for pre-edit ratings where the main effects of monitor and scene were significant. Tables 5 and 6 present the ANOVA summary and mean pre-edit color quality ratings, respectively.

TABLE 5: PILOT STUDY ANOVA SUMMARY TABLE FOR PRE-EDIT COLOR QUALITY RATINGS

Source	DF	SS	MS	F	P
Monitor	2	25709	12855	5.82	0.004
GUI	1	410	410	0.19	0.667
Scene	5	113150	22630	10.24	0.000
Monitor*GUI	2	1009	504	0.23	0.796
Monitor*Scene	10	26182	2618	1.19	0.303
GUI*Scene	5	3719	744	0.34	0.890
Monitor*GUI*Scene	10	5232	523	0.24	0.992
Error	180	397615	2209		
Total	215	573026			

TABLE 6: PILOT STUDY MENAS FOR PRE-EDIT COLOR QUALITY RATINGS BY INTERFACE, MONITOR CALIBRATION, AND SCENE

	Interface		Monitor Calibration			Scene					
	Sliders	Ring-Around	4061-grn	9300	14539-mag	barn	stones	boy	trio	dog	snow
Mean	176.54	179.30	170.54	169.88	193.35	195.86	155.84	208.86	195.50	162.19	149.29
SE	5.18	4.76	6.88	4.84	6.02	9.43	6.12	9.66	8.94	6.26	5.13
N	108	108	72	72	72	36	36	36	36	36	36

Post hoc analyses were conducted using Tukey's honestly significant difference (HSD) test. For the comparisons among scene means, the critical value was 29.736. Only the barn and stones image means differed by more than 29.736 points. No significant differences were found for either the dog-snow comparison or the boy-trio comparison.

Comparisons among the monitor level means were based on a critical value of 17.270. No significant difference was found for the 4061-9300 comparison. However, the 9300-14539 and

4061-14539 comparisons were significantly different. Color quality ratings for the 14539-mag condition exceeded those of the 9300 and 4061-grn conditions.

A second univariate ANOVA was conducted for post-edit ratings where the main effects of monitor and scene were significant. Tables 7 and 8 present the ANOVA summary and mean post-edit color quality ratings, respectively.

TABLE 7: PILOT STUDY ANOVA SUMMARY TABLE FOR POST-EDIT COLOR QUALITY RATINGS

Source	DF	SS	Adj SS	Adj MS	F	P
Monitor	2	17704	17704	8852	5.21	0.006
GUI	1	1688	1688	1688	0.99	0.320
Scene	5	88661	88661	17732	10.43	0.000
Monitor*GUI	2	216	216	108	0.06	0.938
Monitor*Scene	10	9060	9060	906	0.53	0.865
GUI*Scene	5	1262	1262	252	0.15	0.980
Monitor*GUI*Scene	10	3504	3504	350	0.21	0.996
Error	180	306100	306100	1701		
Total	215	428194				

TABLE 8: PILOT STUDY MEANS FOR POST-EDIT COLOR QUALITY RATINGS BY INTERFACE, MONITOR CALIBRATION, AND SCENE

	Interface		Monitor Calibration			Scene					
	Sliders	Ring-Around	4061-grn	9300	14539-mag	barn	stones	boy	trio	dog	snow
Mean	211.54	217.13	206.60	209.37	227.04	231.93	203.81	238.64	231.25	190.86	189.54
SE	4.03	4.54	5.62	3.90	5.79	8.60	5.77	8.02	7.09	5.50	4.17
N	108	108	72	72	72	36	36	36	36	36	36

Post hoc analyses were conducted using Tukey's HSD test. For the comparisons among scene means, the critical value was 30.596. None of the scene pair means differed by more than 30.596 points.

Comparisons among the monitor level means were based on a critical value of 17.769. No significant difference was found for the 4061-9300 comparison. However, both the 9300-14539 and 4061-14539 comparisons yielded significant differences. Once again color quality ratings for photographs presented at the 14539-mag condition were higher than those received under the other conditions.

Red, Green, Blue, Brightness, and Contrast Edits

A MANOVA was conducted for the five edit dimensions across the full factorial design. Significant differences were found for monitor calibration (Wilk's $F_{10,352} = 2.351$, $p = 0.011$), interface (Wilk's $F_{5,176} = 8.202$, $p = 0.000$), and scene (Wilk's $F_{25,655} = 9.786$, $p = 0.000$).

Univariate ANOVAs were then run for each edit dimension with the following outcomes. Significant differences were found among both interface levels and scene levels for red ([interface] $F_{1,180} = 14.40$, $MS_E = 884.12$, $p = 0.000$; [scene] $F_{5,180} = 10.55$, $MS_E = 647.70$, $p = 0.000$), brightness ([interface] $F_{1,180} = 15.50$, $MS_E = 3360.7$, $p = 0.000$; [scene] $F_{5,180} = 14.47$, $MS_E = 3136.6$, $p = 0.000$), and contrast ([interface] $F_{1,180} = 4.84$, $MS_E = 836.2$, $p = 0.029$; [scene] $F_{5,180} = 20.50$, $MS_E = 3542.1$, $p = 0.000$) dimensions. Significant differences among green edits were found for image alone ($F_{5,180} = 4.35$, $MS_E = 155.85$, $p = 0.001$). Finally, blue edits differed substantially among both monitor ($F_{2,180} = 6.17$, $MS_E = 760.3$, $p = 0.003$) and image ($F_{5,180} = 6.70$, $MS_E = 825.3$, $p = 0.000$). Tables 9-13 present mean edit values for each dimension by interface, monitor calibration, and scene.

TABLE 9: PILOT STUDY MEANS FOR RED EDITS BY INTERFACE, MONITOR CALIBRATION, AND SCENE

	Interface		**Monitor Calibration**			**Scene**					
	Sliders	Ring-Around	4061-grn	9300	14539-mag	barn	stones	boy	trio	dog	snow
Mean	-.713	3.33	0.72	2.76	0.44	8.03	-2.06	1.06	2.17	-4.19	2.86
SE	.581	1.04	0.99	1.16	1.00	1.50	1.45	0.79	1.43	1.14	1.66
N	108	108	72	72	72	36	36	36	36	36	36

TABLE 10: PILOT STUDY MEANS FOR GREEN EDITS BY INTERFACE, MONITOR CALIBRATION, AND SCENE

	Interface		**Monitor Calibration**			**Scene**					
	Sliders	Ring-Around	4061-grn	9300	14539-mag	barn	stones	boy	trio	dog	snow
Mean	.963	1.667	0.74	1.24	1.97	1.72	5.25	0.56	0.03	0.92	-0.58
SE	.500	.702	0.71	0.70	0.82	1.65	1.24	0.67	1.03	0.49	0.45
N	108	108	72	72	72	36	36	36	36	36	36

TABLE 11: PILOT STUDY MEANS FOR BLUE EDITS BY INTERFACE, MONITOR CALIBRATION, AND SCENE

	Interface		**Monitor Calibration**			**Scene**					
	Sliders	Ring-Around	4061-grn	9300	14539-mag	barn	stones	boy	trio	dog	snow
Mean	3.324	5.93	7.99	4.39	1.50	0.64	7.42	11.17	-2.19	4.83	5.89
SE	.907	1.32	1.56	1.38	1.13	1.58	1.76	1.96	1.90	1.62	2.22
N	108	108	72	72	72	36	36	36	36	36	36

TABLE 12: PILOT STUDY MEANS FOR BRIGHTNESS EDITS BY INTERFACE, MONITOR CALIBRATION, AND SCENE

	Interface		**Monitor Calibration**			**Scene**					
	Sliders	Ring-Around	4061-grn	9300	14539-mag	barn	stones	boy	trio	dog	snow
Mean	6.00	13.89	10.36	10.22	9.25	20.44	-3.22	2.78	7.28	13.42	18.97
SE	1.23	1.85	1.84	2.07	2.03	3.36	2.38	1.98	1.94	1.79	2.75
N	108	108	72	72	72	36	36	36	36	36	36

TABLE 13: PILOT STUDY MEANS FOR CONTRAST EDITS BY INTERFACE, MONITOR CALIBRATION, AND SCENE

	Interface		**Monitor Calibration**			**Scene**					
	Sliders	Ring-Around	4061-grn	9300	14539-mag	barn	stones	boy	trio	dog	snow
Mean	11.81	15.74	14.40	14.31	12.61	-0.36	30.61	13.39	14.81	11.14	13.06
SE	1.15	1.80	1.86	2.01	1.72	2.35	3.00	2.05	1.89	1.58	1.93
N	108	108	72	72	72	36	36	36	36	36	36

Post hoc analyses were conducted for scene and monitor using Tukey's HSD test. The scene comparisons of primary interest were those within each class (i.e., differences between the barn-stones pair, the dog-snow pair, and the boy-trio pair). Red editing behavior differed significantly between the barn and stones scenes as well as between the dog and snow scenes (critical difference > 5.289). None of the three scene pairs was found to differ significantly with respect to green editing behavior (critical difference > 4.111). Blue edits varied significantly only among the boy-trio pair (critical difference > 7.243). Finally, the barn-stones pair was found to elicit significantly different editing behavior for both brightness (critical difference > 9.475) and contrast (critical difference > 8.729) dimensions.

Comparisons among the monitor level means indicated that the only editing dimension to exhibit differential behavior was the blue dimension. For this case, editing differed significantly for the 4061grn-14539mag pair (critical difference > 4.207). Differences for the 9300-4539mag and 4061grn-9300 pairs were not significant.

In addition to the main effects outlined above, two interactions were statistically significant: the Scene x Interface effect for both red edits ($F_{5,180} = 2.47$, $MS_E = 61.41$, $p = 0.034$) and contrast edits ($F_{5,180} = 2.33$, $MS_E = 172.8$, $p = 0.044$). In each case, edits were of a greater magnitude with the ring-around interface and limited to particular scenes. The barn and snow scenes received larger increases in red when edited with the ring-around interface rather than the slider interface. The difference between average red edits between the ring-around and slider interfaces was less than 5 units for all other scenes. Similarly, increases in contrast for the Stones scene were much larger with the ring-around version of the color tool than with the slider version. The remaining five scenes exhibited no differences in contrast adjustments between the interfaces.

Discussion

Interface

It would seem that no one interface afforded users an advantage with respect to generating high quality color images. This was evidenced by the fact that color quality ratings did not vary systematically by interface. In addition, an ANOVA was conducted for the change in rating

between the pre-edit and the post-edit data. This delta-edit analysis yielded nonsignificant results for interface ($F_{1,180}$ = 0.00, MS_E = 711.5, p = 0.979). Thus, neither interface afforded users with an editing advantage resulting in higher perceived color quality.

The time required to edit an image was expected to vary by interface, and was considered the primary selection criteria between the two. Since the main study would present participants with over 100 images, it was of interest to establish procedures and tools to minimize time. To this end, the ring-around interface had a distinct benefit over the slider interface. Though the mean time difference was relatively small (i.e., 21 s), over the course of the larger study the cumulative savings could be substantial (i.e., 33 min).

The significance of red edits by interface, as well as the two interaction effects, was likely caused by the difference in step size between the interfaces: The sliders allowed increases / decreases by single units, whereas the ring-around forced increases / decreases in 20 unit steps. In each case, the average edit magnitude was larger for the ring-around interface than the slider interface. This trend indicated a fine / course option would be desirable for the ring-around interface.

Monitor

The monitor settings varied not only in color temperature but in excitation purity as well. The former would be expected to influence editing behavior in the blue-yellow dimension, while the influence of purity would be expected in the green-magenta editing dimension. Because the only editing dimension influenced by the monitor was the blue-yellow dimension, it appeared the influence of purity did not play a role in the editing behavior of the participants. This does not mean purity has no effect on color images, only that the level presented herein (i.e., equal to a ΔE_{uv^*}= 15), combined with the color temperatures, gamma levels, and viewing conditions used did not significantly influence editing behavior.

However, participants were influenced by the color temperature of the monitor. Color quality ratings were higher for the higher color temperatures. In addition, the 14539 K-mag setting elicited less introduction of blue during color editing than the 4061 K setting. This would be expected, as higher temperatures tend to create a blue appearance on-screen and lower temperatures a warmer, yellow appearance. Even though more blue was added at the lower color temperature, the post-edit ratings at 4061 K-grn were still significantly lower than those for the 14539 K-mag setting. The disparity between post-edit ratings may be attributable to chromatic adaptation mechanisms or personal preferences. In the former case, chromatic adaptation may have been less complete at the lower color temperature, resulting in a persistent and objectionable perception of yellow (Fairchild, 1993; Hunt, 1980; Gorzynski and Berns, 1990). Alternatively, participants may have preferred photographs presented with a

blue bias relative to those presented with a yellow bias. Particularly if they perceived the photographs presented under 14539-mag to be of greater luminance (Breneman and Witzel, 1962).

Scene

Because editing behavior and its influence on hardcopy output was of interest for the primary study, it was desirable to select quality scenes that were not viewed as perfect by participants. Rather, scenes that were deemed improvable by participants would be preferred stimuli, as they would be accompanied by a some degree of editing behavior. The barn, boy and dog scenes were more heavily edited than their scene-class counterparts. The differences in editing behavior observed for the scene pairs may have been due to inherent color balance (at the time of original scan from film to PhotoCD), scene content, or some combination there of. This distinction was difficult to make given the data collected nor was this question of interest. However, the post hoc analyses indicated there were differences among scene pairs. Given the desire to use scenes that encouraged some level of editing, the barn, boy, and dog scenes were the more attractive alternatives. In addition each of these photographs received, on average, a higher color quality rating, both prior to editing and after editing, than their scene-class counterparts.

PRIMARY STUDY

Methods

Participants

Twenty-four participants were recruited from within Eastman Kodak Company in Rochester, NY. The 14 men and 10 women ranged in age from 22 to 55 years. All individuals were screened for participation, based on the following selection criteria;

- normal color vision (0 misses on Pseudoisochromatic Plate test),
- normal corrected, binary, visual acuity (≥ 20/30),
- frequent photographer (≥ 10 rolls/yr.),
- exposure to and interest in electronic imaging and on-screen viewing of imagery, either from home or from work,
- specific upcoming event to photograph,
- no performance of color quality evaluations as part of his/her job.

Two participants withdrew from the study prior to its completion. All statistical analyses were limited to the data collected from the remaining 22 participants (13 men, 9 women). Participants were compensated with Kodak products and services.

Images, Apparatus, and Environment

Images: Images were selected from two sources; first-party images captured by the participants themselves, and third-party images from Kodak photographic databases. First-party photographs afford the benefits of memory for the original scene and its colors, emotional connection to image content, and a personal interest in attaining high image quality. To acquire first-party photos, one roll of Kodak Gold, 400 speed, 35mm film was handed out to each participant for use between December 19th, 1997 and January 5th, 1998. This film was developed, processed, and written to PhotoCD, by the Pilot Laboratory in Building 69 of Kodak Park. Three photographs were selected from each participant's processed film. Selection was based on overall image quality as determined by a Kodak Image Evaluation Program (IEP) technician. An IEP technician eliminated any photographs containing problems, as defined by IEP problem boards, and from the remaining photographs, chose the three highest quality images (i.e., those with the highest Q_a rating) (Appendix E).

In order to ensure each participant viewed at least three high quality images as well as images containing common memory colors, three third-party photographs--those taken by an

individual unknown to the participant--were selected. Selection of third-party photographs was based on the findings obtained in Experiment I. The pilot study indicated the barn, boy, and dog scenes would be appropriate stimuli for the primary study (Appendix A). However, dirt was discovered on the barn scene that could not be digitally removed prior to commencement of the study. Hence, the stones scene, containing green grass and blue sky, was substituted. The second scene, boy, had a compositional emphasis on skintones. The third scene, dog, consisted primarily of various shades of gray, from white to black. The original film type for each third-party image was unknown.

A series of image processing steps were required to render the photographs first in softcopy and later in hardcopy (Appendix B). All first- and third-party images were initially processed from PhotoCD to monitor RGB values for presentation on a CRT display. Images were then processed from monitor RGB values to printer densities for presentation in a silver halide medium. Image processing was carried out using Kodak internal software. In addition, Matlab (v5.0 for UNIX) was used to generate some of the tables and matrices required for transformation.

Photographic quality prints were made for each photograph presented in softcopy. In addition, a null photograph was printed for each first-party and third-party image. The null represented the hardcopy print that would be created if no edits had been made during the softcopy phase. Printing occurred in two stages. Sensitized paper was exposed using a Kodak Digital Science Large Format CRT color printer (LFCRT). A rapid access (RA4) developing process was employed after exposure to create image formation on Kodak Ektacolor Edge 7 paper.

Editing Software: A software color tool, developed in-house, allowed participants to adjust on-screen color appearance of images. The color tool presented images single stimulus for rating and editing. It provided participants with the ability to adjust red, green, blue, brightness, and contrast dimensions of color appearance. Color balancing was accomplished using a modified ring-around graphical user interface with fine/gross adjustment capabilities (Appendix C).

Display Systems: Photographs were presented on two Sony 17seII CRT displays coupled with a PowerMac 8100/100av. Both displays were visually inspected for relative, gross performance differences in sharpness, flicker, jitter, and uniformity, using a SMPTE test pattern. No gross performance differences were observed. The active display area size, centering, and convergence were held constant between displays. All images were presented at an addressability of 832 x 624 and a color depth of 24 bits. The monitor settings (Appendix F)

were achieved through physical manipulation of monitor hardware per the procedure described under PILOT STUDY (page 39).

Viewing Environment: All softcopy and hardcopy image viewing took place in one room (Figure 15). The walls, floor, and desktop surfaces of the room were covered in a medium gray material to produce a dim ambient surround. Illumination was provided by four incandescent lamps. Source selection was based on the general dominance of incandescent sources over fluorescent sources in the home environment. The front lamps were set to 50 watts and the rear lamps to 100 watts, such that they produced 21 lux of ambient illumination at the desktop, in front of the monitor. This level was representative of that found in consumer homes during a recent Kodak investigation (Cottone & Miller, 1997).

FIGURE 15: VIEWING ENVIRONMENT

The top photograph details the boxed area depicted on the plan below. Overall room dimensions were 13'4" wide by 15'4" deep. Lamps were placed symmetrically about the display. Care was taken to prevent either direct or reflected glare at the work center. The CRT faceplate was positioned 12" from the front edge of the desktop. Participants were free to position themselves comfortably at the work center thus, eye-to-screen distance was not strictly controlled.

Experimental design

Independent Variables: Three independent variables were selected for manipulation: CRT gamma, correlated color temperature, and excitation purity. Each of these factors contributes

to the color balance of the display and can be manipulated independent of the others. The range of each variable was selected based on data collected by Kodak in retail computer stores and consumer homes (Cottone, 1996; Cottone & Miller, 1997). Gamma was manipulated between 1.0 and 3.0. Correlated color temperature ranged from 4061 K to 14539 K. Excitation purity extended from -12 ΔE^*_{uv} to +12 ΔE^*_{uv}.

The CIE 1976 $L^*u^*v^*$ color difference formula (i.e., ΔE^*_{uv}) was used to define purity as the Euclidean distance between a point on the blackbody curve and a point along an associated isotemperature line (Figure 16). The CIE 1976 UCS chromaticity coordinates (u', v') and lightness (Y) were determined for a point on the blackbody curve (u'_n, v'_n, Y_n) and a second point on the isotemperature line (u', v' , Y). These values were converted to rectangular coordinates in the CIE 1976 L*u*v* color space (CIELUV) using Equation (2):

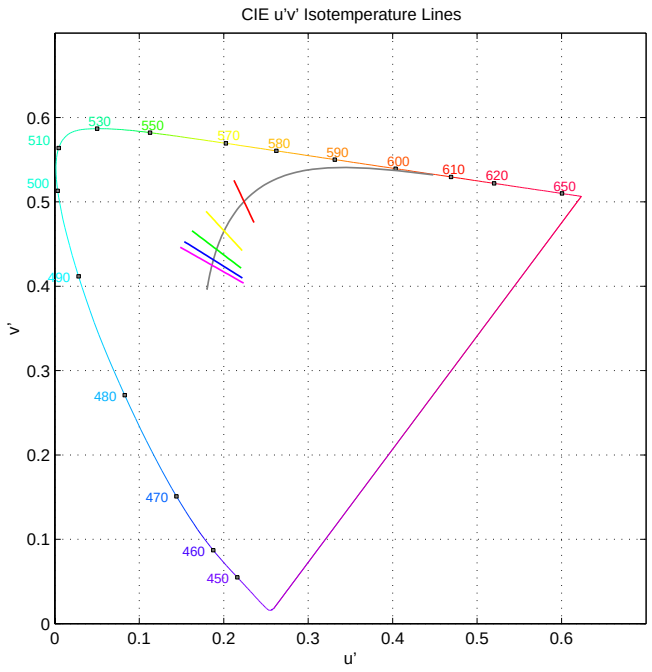
$$
\begin{aligned}
L^* &= 116(Y/Y_n)^{1/3} - 16 \qquad \text{when } Y/Y_n > 0.008856 \\
L^* &= 903.3(Y/Y_n) \qquad \text{when } Y/Y_n \le 0.008856 \\
u^* &= 13L^*(u' - u'_n) \\
v^* &= 13L^*(v' - v'_n)
\end{aligned}
\tag{2}
$$

The difference between CIELUV coordinates for the blackbody point and the isotemperature point were then used to calculate ΔE^*_{uv} per Equation (3):

$$
\Delta E^*_{uv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2} \tag{3}
$$

FIGURE 16: ISOTEMPERATURE LINES ON A CIE 1976 UCS DIAGRAM

Six isotemperature lines are presented. From upper-right to lower-left the correlated color temperatures for each line are 4061 K, 6500 K, 9300 K, 12100 K and 14539 K. Color temperatures below about 5500 K appear warm (i.e., yellow). Those above 6500 K appear cool (i.e., blue). Between 5500 K and 6500 K a neutral appearing white is generally obtained. Appearance of isotemperature points above the BBC is green while those below the BBC are magenta.



Design: A within-subjects approach was selected in conjunction with a spherical central composite design (CCD). Treatment presentation could not be completed in one session. Therefore, a blocked CCD configuration was employed, with sessions as the blocking factor. For blocked designs on three factors, with one center point replication, the alpha (α) value is $\pm$ 1.871 (Myers & Montgomery, 1995). Table 14 provides a listing of the factors and their levels at each of the CCD points (i.e., $\pm \alpha$, $\pm$ 1, and 0). Block 1 was comprised of the factorial portion of the CCD. Block 2 was comprised of the axial design points and one replication of the center point. The resulting 15 within-subjects treatment conditions are presented in Table 15. Participants viewed all scenes under each treatment condition. Presentation of treatments and scenes was completely randomized.

TABLE 14: BLOCKED CCD INDEPENDENT VARIABLES AND LEVELS

	- 1.871 (α)	**-1**	**0**	**+1**	**+ 1.871 (α)**
Gamma	1.0	1.46	2.0	2.53	3.0
Color Temperature (K)	4061	6500	9300	12100	14539
Purity (ΔE^*_{uv})	-12	-6	0	6	12

TABLE 15: BLOCKED CCD TREATMENT CONDITIONS

Participants	**Block**	**Treatment**	**Gamma**	**Purity**	**Color Temperature**
1 - 22	1	1 [224]	-1	-1	+1
1 - 22	1	2 [222]	-1	-1	-1
1 - 22	1	3 [244]	-1	+1	+1
1 - 22	1	4 [242]	-1	+1	-1
1 - 22	1	5 [424]	+1	-1	+1
1 - 22	1	6 [422]	+1	-1	-1
1 - 22	1	7 [444]	+1	+1	+1
1 - 22	1	8 [442]	+1	+1	-1
1 - 22	2	9 [533]	$+\alpha$	0	0
1 - 22	2	10 [133]	$-\alpha$	0	0
1 - 22	2	11 [353]	0	$+\alpha$	0
1 - 22	2	12 [313]	0	$-\alpha$	0
1 - 22	2	13 [335]	0	0	$+\alpha$
1 - 22	2	14 [331]	0	0	$-\alpha$
1 - 22	2	15 [333]	0	0	0

Procedure

The experiment was divided into three primary phases, requiring four separate visits on the part of the participant. In phase one, participants were recruited in accordance with the selection criteria and scheduled for an orientation session. Orientation involved the

communication of information regarding the study, participant responsibilities, responsibilities of the experimenter, and guidelines for participation. Each participant also was given two five minute, visual tests: one for binary acuity (using an Orthorater device) the other for gross color vision deficits (using a Pseudoisochromatic Plate test). Participants then were issued a roll of film to expose over a 14 day period and return for processing.

Phase two encompassed softcopy image viewing and manipulation. Participants first were asked to provide a personal definition of color quality followed by a description of a high color quality photograph they were familiar with (Appendix D). This imagined reference image was assigned a value of 200 (Appendix G). All experimental photographs were given a color quality rating proportional to the modulus, using a free-modulus magnitude estimation technique[4]. All softcopy images were assigned a color quality rating based on the color quality of the participant's imagined reference image. A photograph was presented single stimulus during the evaluation stage, then redrawn on an editing screen where the participant was given the opportunity to adjust color balance. The goal for this stage of the study was for participants to achieve the best possible color balance based on their own personal preferences.

The softcopy phase of the study was broken into two sessions. During their first visit, participants spent approximately three hours evaluating and editing images for block 1 of the experimental conditions. Participants returned one week later for a second three-hour editing and manipulation session in which the remaining experimental conditions were presented.

The final phase consisted of color quality evaluations of hardcopy images. Each image edited during the softcopy phase was printed out for viewing and evaluation. These prints reflected the editing that occurred on-screen (e.g., if one added magenta to balance a softcopy image, the hardcopy print would appear magenta compared with the unedited hardcopy, or null, image). Participants again provided subjective color quality ratings in relation to their imagined reference photo, using a free-modulus magnitude estimation technique. Hardcopy prints were viewed single stimulus against a medium gray background.

Next, participants were asked to rank order the variations of each scene, from most preferred to least preferred. Each scene contained sixteen prints; one for each treatment and the null photograph. One scene was presented to the participant at a time. Prints were spread out before the participant who ordered them on the desktop from most preferred color quality to least preferred color quality. Finally, when the participant had settled on a rank order, he/she was asked to indicate where, if at all, color quality became unacceptable. All prints were viewed against a medium gray background.

[4] Though the modulus was fixed at a value of 200, each participant's imagined reference was different from the others, both in content, composition, and color quality. Hence, the procedure was in essence a free-modulus magnitude estimation technique.

Results

Dependent Measures

Nine dependent measures were recorded: pre-edit ratings, red, green, blue, brightness, and contrast edits, free-modulus hardcopy color quality ratings, rank-order hardcopy color quality preferences, and hardcopy color quality acceptance ratings. Unadjusted color quality ratings fell between 30 and 300 for softcopy and 10 and 270 for hardcopy. Edit magnitudes ranged from -60 to 140, with positive numbers denoting increases and negative numbers denoting decreases.

Five main analyses were conducted on the dependent variables. Of particular interest were whether; (i) softcopy color quality, (ii) editing behavior, (iii) hardcopy color quality, and (iv) hardcopy color quality preferences varied by monitor calibration. The final analysis of interest was the prediction of hardcopy rejection rates from CRT calibration. Unless indicated otherwise, all hypothesis tests were conducted at an alpha level of 0.05 with statistical analyses performed by JMP (v3.1.6 for Macintosh). Means and predicted values for all parametric tests are presented in Appendix H. A complete listing of reduced regression models, based only on significant parameters, is provided in Appendix I.

Data Reduction

Three sources contributed to data variance; party differences, scene differences, and individual differences. Party differences arose as a consequence of using both familiar and unfamiliar photographs during data collection. Participants may be expected to treat photographs differently based on the degree to which they have a personal interest in the subject matter. Another source of variance lies with each participant's personal preference for optimal color balance. Each individual may define color quality differently and may employ different strategies to achieve good color quality. Furthermore, decisions about color quality and editing behavior may be driven by the content and characteristics of the photograph. Thus, each photo may be treated differently by the participant. Though party, individual, and scene differences potentially influenced the responses solicited from participants, it was not the intention of this study to document or quantify their effects. It was assumed these factors contributed to the experimental variance. However, their contributions were minor relative to the CRT parameters manipulated. In order to focus on the effects of primary interest, steps were taken to reduce the influence of party, scene, and individual differences on the dataset.

The design structure differed for first-party (nested) and third-party (crossed) photographs prohibiting their simultaneous inclusion in one complex model. Consequently, first-party and

third-party data were treated separately for each statistical test performed. Within each party subset, there remained two sources of variation. Each data subset was collapsed by taking the arithmetic average of all dependent measures across scene and participant. Averaging the data in this manner was statistically equivalent to treating these factors as parameters in a complex model (M. Dupin, personal communication, September, 1998). If a complex model had been generated, each factor would be associated with some portion of the total variance and degrees of freedom. Averaging dampened the variance in the remaining data and reduced the degrees of freedom. This approach was adopted for simplicity and was possible because there was no desire to quantify the effects of scene or individuals.

Softcopy Color Quality

Color quality ratings were transformed using the procedure described under PILOT STUDY (page 41). The transformed color quality ratings were separated by party then averaged across participant and scene. Factor levels were represented in coded units (i.e., $\pm\alpha$, ±1, 0) and analyzed using a quadratic response-surface regression. First-party and third-party analyses both indicated a significant effect for gamma and gamma^2 components (Tables 16 and 17). Higher softcopy color quality ratings were achieved at higher gamma levels. In addition, color temperature exhibited a significant affect on softcopy color quality ratings for third-party photographs. Again, higher color temperatures were associated with higher perceived color quality. These results indicate that participants deemed photographs to be better in color quality when picture elements were brighter, bluer, and had higher apparent contrast.

TABLE 16: FIRST-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR SOFTCOPY CQ RATINGS (MSE = 21.25 R^2 = 0.95)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	166.01768	5.175358	32.08	<.0001
block[1-2]	-1.372882	1.393278	-0.99	0.3802
gamma	9.8766243	1.191312	8.29	0.0012
purity	-0.254582	1.191312	-0.21	0.8412
temp	-0.09754	1.191312	-0.08	0.9387
gamma*gamma	-4.303248	1.800107	-2.39	0.0751
purity*gamma	1.0729316	1.631341	0.66	0.5467
purity*purity	-0.831241	1.800107	-0.46	0.6682
temp*gamma	1.1188261	1.631341	0.69	0.5305
temp*purity	-0.68948	1.631341	-0.42	0.6943
temp*temp	-2.162533	1.800107	-1.20	0.2959

TABLE 17: THIRD-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR SOFTCOPY CQ RATINGS (MSE = 12.67 R^2 = 0.97)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	168.57113	3.998897	42.15	<.0001
block[1-2]	1.1856877	1.076558	1.10	0.3326
gamma	8.353014	0.920503	9.07	0.0008
purity	-1.699601	0.920503	-1.85	0.1386
temp	3.3957112	0.920503	3.69	0.0210
gamma*gamma	-3.701937	1.390907	-2.66	0.0563
purity*gamma	0.236413	1.260505	0.19	0.8604
purity*purity	0.828915	1.390907	0.60	0.5833
temp*gamma	1.0260475	1.260505	0.81	0.4613
temp*purity	-0.882115	1.260505	-0.70	0.5226
temp*temp	-1.952136	1.390907	-1.40	0.2331

Softcopy Editing Behavior

Edits were separated by party then averaged across participant and scene. Factor levels were represented in coded units and analyzed using a quadratic response-surface regression.

Red Edits: Both first-party and third-party analyses revealed a significant main effect for color temperature (Tables 18 and 19). Higher color temperatures elicited increases in red while lower color temperatures brought about decreases in red. The first-party analysis also indicated a significant main effect for purity. Purity levels above the blackbody curve were associated with larger additions of red, than those on or below the blackbody curve.

These results indicate that participants perceived the overall color balance differences induced by color temperature and purity, and responded to these differences by adjusting red balance. The direction of their edits effectively warmed photographs presented with a green-blue bias and cooled photographs presented with a yellow-red bias.

TABLE 18: FIRST-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR RED EDITS (MSE = 1.68 R^2 = 0.92)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.2607557	1.454615	0.87	0.4350
block[1-2]	-0.260756	0.391603	-0.67	0.5419
gamma	-0.334505	0.334837	-1.00	0.3743
purity	1.1271748	0.334837	3.37	0.0281
temp	1.5465585	0.334837	4.62	0.0099
gamma*gamma	-0.07756	0.505948	-0.15	0.8856
purity*gamma	0.3846154	0.458514	0.84	0.4488
purity*purity	0.3227991	0.505948	0.64	0.5582
temp*gamma	0.2884615	0.458514	0.63	0.5634
temp*purity	0.5	0.458514	1.09	0.3368
temp*temp	-0.918316	0.505948	-1.82	0.1437

TABLE 19: THIRD-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR RED EDITS
(MSE = 1.77 R^2 = 0.90)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.607879	1.493544	-1.08	0.3423
block[1-2]	0.0878787	0.402083	0.22	0.8377
gamma	-0.318081	0.343798	-0.93	0.4072
purity	0.6657978	0.343798	1.94	0.1249
temp	1.3515545	0.343798	3.93	0.0171
gamma*gamma	0.3001615	0.519489	0.58	0.5944
purity*gamma	3.737e-14	0.470785	0.00	1.0000
purity*purity	0.224461	0.519489	0.43	0.6880
temp*gamma	-0.245	0.470785	-0.52	0.6303
temp*purity	0.605	0.470785	1.29	0.2681
temp*temp	-0.879622	0.519489	-1.69	0.1657

Green Edits: First-party analysis yielded a significant main effect for temperature as well as a significant interaction between color temperature and gamma (Table 20). Higher color temperatures induced a larger addition of green than lower temperatures. Though no main effects achieved statistical significance for third-party data, the interaction between color temperature and purity was significant (Table 21).

These results indicate participants perceived the overall color balance differences induced by color temperature, and responded to these differences by adjusting green balance. However, their editing behavior was inconsistent across the temperature spectrum, depending both on purity level and gamma level.

TABLE 20: FIRST-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR GREEN EDITS
(MSE = 0.17 R^2 = 0.91)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.3756887	0.468556	0.80	0.4676
block[1-2]	0.316619	0.126142	2.51	0.0661
gamma	-0.098521	0.107857	-0.91	0.4127
purity	-0.142771	0.107857	-1.32	0.2562
temp	0.4352446	0.107857	4.04	0.0157
gamma*gamma	0.2319982	0.162975	1.42	0.2277
purity*gamma	0.2884615	0.147695	1.95	0.1225
purity*purity	0.3402035	0.162975	2.09	0.1051
temp*gamma	0.4423077	0.147695	2.99	0.0401
temp*purity	0.0576923	0.147695	0.39	0.7160
temp*temp	0.2547213	0.162975	1.56	0.1931

TABLE 21: THIRD-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR GREEN EDITS
(MSE = 0.14 R^2 = 0.86)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.5721751	0.414572	1.38	0.2397
block[1-2]	0.2578249	0.111608	2.31	0.0820
gamma	-0.026773	0.09543	-0.28	0.7930
purity	-0.124787	0.09543	-1.31	0.2611
temp	0.0750263	0.09543	0.79	0.4757
gamma*gamma	0.0287518	0.144198	0.20	0.8517
purity*gamma	0.24625	0.130679	1.88	0.1326
purity*purity	0.061603	0.144198	0.43	0.6912
temp*gamma	0.01875	0.130679	0.14	0.8928
temp*purity	0.45375	0.130679	3.47	0.0255
temp*temp	0.0258952	0.144198	0.18	0.8662

Blue Edits: Both first-party and third-party analyses revealed a significant main effect for color temperature (Tables 22 and 23). Lower color temperatures elicited larger subtractions of blue than did higher color temperatures. The third-party analysis also indicated a significant effect for the quadratic color temperature term.

These results indicate that participants perceived the overall color balance differences induced by color temperature, and responded to these differences by adjusting blue balance. The direction of their edits effectively warmed photographs presented with a blue bias and cooled photographs presented with a yellow bias.

TABLE 22: FIRST-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR BLUE EDITS
(MSE = 3.94 R^2 = 0.80)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.220458	2.228436	-0.55	0.6130
block[1-2]	0.1435353	0.599926	0.24	0.8227
gamma	-0.04719	0.512962	-0.09	0.9311
purity	0.2928561	0.512962	0.57	0.5986
temp	-1.509666	0.512962	-2.94	0.0423
gamma*gamma	0.0001021	0.775101	0.00	0.9999
purity*gamma	0.125	0.702432	0.18	0.8674
purity*purity	-0.151385	0.775101	-0.20	0.8547
temp*gamma	-0.490385	0.702432	-0.70	0.5236
temp*purity	-0.201923	0.702432	-0.29	0.7880
temp*temp	1.1416679	0.775101	1.47	0.2148

TABLE 23: THIRD-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR BLUE EDITS
(MSE = 1.98 R^2 = 0.95)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	7.1843474	1.579742	4.55	0.0104
block[1-2]	0.0856526	0.425288	0.20	0.8502
gamma	-0.400074	0.36364	-1.10	0.3330
purity	0.873628	0.36364	2.40	0.0742
temp	-2.398636	0.36364	-6.60	0.0027
gamma*gamma	-0.112464	0.54947	-0.20	0.8478
purity*gamma	0.32125	0.497956	0.65	0.5540
purity*purity	-0.156741	0.54947	-0.29	0.7896
temp*gamma	-0.13375	0.497956	-0.27	0.8015
temp*purity	-0.05625	0.497956	-0.11	0.9155
temp*temp	1.5029548	0.54947	2.74	0.0522

Brightness Edits: Both first-party and third-party analyses revealed a significant main effect for gamma (Tables 24 and 25). Generally speaking, brightness edits increased with increasing gamma levels. The first-party analysis also indicated significant effects for block, $gamma^2$, and the color temperature-purity interaction.

These results indicate participants perceived brightness differences induced by the CRT gamma value, and responded to these differences by adjusting image brightness. Their edits lightened photographs presented with high apparent contrast.

TABLE 24: FIRST-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR BRIGHTNESS EDITS (MSE = 0.78 R^2 = 0.97)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	11.215085	0.994229	11.28	0.0004
block[1-2]	0.9387609	0.26766	3.51	0.0247
gamma	1.440542	0.228861	6.29	0.0033
purity	0.118979	0.228861	0.52	0.6306
temp	-0.532693	0.228861	-2.33	0.0805
gamma*gamma	-1.312476	0.345815	-3.80	0.0192
purity*gamma	0.5480769	0.313394	1.75	0.1552
purity*purity	-0.771449	0.345815	-2.23	0.0895
temp*gamma	0.2019231	0.313394	0.64	0.5545
temp*purity	-1.394231	0.313394	-4.45	0.0113
temp*temp	-0.887229	0.345815	-2.57	0.0623

TABLE 25: THIRD-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR BRIGHTNESS EDITS (MSE = 1.04 R^2 = 0.92)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2.8293555	1.143066	2.48	0.0686
block[1-2]	0.3506445	0.307729	1.14	0.3181
gamma	1.5155805	0.263122	5.76	0.0045
purity	-0.009506	0.263122	-0.04	0.9729
temp	-0.329476	0.263122	-1.25	0.2787
gamma*gamma	-0.318145	0.397584	-0.80	0.4684
purity*gamma	-0.1225	0.360309	-0.34	0.7510
purity*purity	0.1574823	0.397584	0.40	0.7123
temp*gamma	0.1225	0.360309	0.34	0.7510
temp*purity	-0.8975	0.360309	-2.49	0.0674
temp*temp	0.3431626	0.397584	0.86	0.4368

Contrast Edits: Both first-party and third-party analyses revealed a significant main effect for gamma (Tables 26 and 27). As gamma level increased the amount of contrast added was reduced. The third-party analysis also indicated a significant main effect for block.

These results indicate that participants perceived apparent contrast differences induced by the CRT gamma value, and responded to these differences by adjusting image contrast. The direction of their edits boosted apparent contrast at all gamma levels, but to a much greater degree when the apparent contrast of the photographs was low.

TABLE 26: FIRST-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR CONTRAST EDITS (MSE = 11.82 R^2 = 0.98)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	18.47557	3.856948	4.79	0.0087
block[1-2]	-2.090955	1.038344	-2.01	0.1143
gamma	-10.79813	0.887828	-12.16	0.0003
purity	0.1676558	0.887828	0.19	0.8594
temp	1.2595306	0.887828	1.42	0.2290
gamma*gamma	2.1753996	1.341534	1.62	0.1802
purity*gamma	-0.115385	1.215761	-0.09	0.9290
purity*purity	-0.648758	1.341534	-0.48	0.6540
temp*gamma	-0.519231	1.215761	-0.43	0.6913
temp*purity	-0.076923	1.215761	-0.06	0.9526
temp*temp	-1.045872	1.341534	-0.78	0.4792

TABLE 27: THIRD-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR CONTRAST EDITS (MSE = 5.10 R^2 = 0.99)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	21.785098	2.53372	8.60	0.0010
block[1-2]	-2.315098	0.682113	-3.39	0.0274
gamma	-9.664681	0.583235	-16.57	<.0001
purity	0.2659993	0.583235	0.46	0.6720
temp	0.9480536	0.583235	1.63	0.1794
gamma*gamma	2.2481037	0.881286	2.55	0.0632
purity*gamma	-0.16	0.798662	-0.20	0.8510
purity*purity	-0.575665	0.881286	-0.65	0.5493
temp*gamma	-0.275	0.798662	-0.34	0.7479
temp*purity	-1.2775	0.798662	-1.60	0.1849
temp*temp	-0.639939	0.881286	-0.73	0.5080

Hardcopy Color Quality

Color quality ratings were transformed using the procedure described under PILOT STUDY (page 42). Transformed color quality ratings then were averaged across participant and scene. Factor levels were represented in coded units and analyzed using a quadratic response-surface regression.

First-party and third-party analyses both indicated a significant effect for gamma (Tables 28 and 29). In general, perceived hardcopy color quality increased with higher gamma levels. These results indicate that participants deemed photographs to be better in color quality when picture elements had received minimal editing. The higher color quality ratings at higher gamma levels may be attributed to the fact that contrast was adjusted to a lesser degree when apparent contrast was high. Consequently, the digital values of the images were altered to a lesser extent, resulting in a print with less degradation.

Color temperature and block effects reached significance for color quality ratings of third-party photographs. In relation to third-party photos, lower color temperatures generally elicited higher color quality ratings and larger additions of blue and cyan than did higher temperatures. This suggests participants had a preference for prints biased in the blue-cyan direction.

TABLE 28: FIRST-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR HARDCOPY CQ RATINGS (MSE = 13.03 R^2 = 0.93)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	165.32857	4.047247	40.85	<.0001
block[1-2]	1.0898266	1.089575	1.00	0.3738
gamma	5.5140008	0.931633	5.92	0.0041
purity	-1.499908	0.931633	-1.61	0.1827
temp	1.5122004	0.931633	1.62	0.1799
gamma*gamma	-1.816437	1.407725	-1.29	0.2665
purity*gamma	-2.103205	1.275746	-1.65	0.1746
purity*purity	-0.173804	1.407725	-0.12	0.9077
temp*gamma	1.6466685	1.275746	1.29	0.2663
temp*purity	1.867355	1.275746	1.46	0.2171
temp*temp	-0.458168	1.407725	-0.33	0.7611

TABLE 29: THIRD-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR HARDCOPY CQ RATINGS (MSE = 6.97 R^2 = 0.98)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	141.661	2.95754	47.90	<.0001
block[1-2]	2.6102296	0.796211	3.28	0.0305
gamma	9.2616183	0.680794	13.60	0.0002
purity	-0.978271	0.680794	-1.44	0.2241
temp	-2.120696	0.680794	-3.12	0.0357
gamma*gamma	-1.457761	1.0287	-1.42	0.2294
purity*gamma	-0.676776	0.932256	-0.73	0.5081
purity*purity	1.6997609	1.0287	1.65	0.1738
temp*gamma	-0.476155	0.932256	-0.51	0.6364
temp*purity	0.5754786	0.932256	0.62	0.5704
temp*temp	1.5636138	1.0287	1.52	0.2031

Hardcopy Preference Rankings

Prints rated by participants as having the highest CQ were assigned a rank of 1. As CQ declined, ranks increased to a maximum score of 16. A Friedman two-way ANOVA by ranks was conducted on the rank-order preference ratings of first-party and third-party datasets, separately. Due to missing values, data from four participants were excluded from the first-party analysis while, three participants were excluded from the third-party analysis.

Results indicated a statistical difference was present between at least one pair of treatments for both first-party (F_r (N=18x3 k=16) = 118.2, $p < 0.001$) and third-party (F_r (N=19x3 k=16) = 187.1, $p < 0.001$) datasets. A multiple comparison test then was conducted using the following criterion (Siegel & Castellan, 1988):

$$|R_u - R_v| \quad z_{\alpha/k(k-1)} [(Nk(k-1))/6]^{1/2} \qquad (4)$$

In this equation, u and v index a particular sum-of-ranks table row and column, respectively. N is the number of participants and k is the number of items ranked. Based on an alpha level of 0.05, critical differences for first- and third-party data were 177.9 and 173.2, respectively. Comparison results for each party are presented in Tables 30 and 31 with significant differences in red typeface.

A Kendall Coefficient of Concordance (W) was calculated for each dataset. The result was a value of 0.138 for first-party photographs and 0.231 for third-party photographs. A significance test on W indicated the rankings provided by various participants for first-party photos (χ^2 (15, N = 18x3) = 37.7, $p < 0.001$) and third-party photos (χ^2 (15, N = 19x3) = 37.7, $p < 0.001$) could not be deemed unrelated. This result implies that, as a group, participants were in agreement with respect to their preferences for hardcopy color quality.

TABLE 30: SUM OF RANKS MULTIPLE COMPARISONS FOR FIRST-PARTY HARDCOPY PREFERENCE RANKINGS

Treatment		224	222	244	242	424	422	444	442	533	133	353	313	335	331	333	null
	Sum of Ranks	500	532	618	617	428	445	446	423	336	694	462	508	505	492	452	294
224	500	0															
222	532	32	0														
244	618	118	86	0													
242	617	117	85	1	0												
424	428	72	104	190	189	0											
422	445	55	87	173	172	17	0										
444	446	54	86	172	171	18	1	0									
442	423	77	109	195	194	5	22	23	0								
533	336	164	196	282	281	92	109	110	87	0							
133	694	194	162	76	77	266	249	248	271	358	0						
353	462	38	70	156	155	34	17	16	39	126	232	0					
313	508	8	24	110	109	80	63	62	85	172	186	46	0				
335	505	5	27	113	112	77	60	59	82	169	189	43	3	0			
331	492	8	40	126	125	64	47	46	69	156	202	30	16	13	0		
333	452	48	80	166	165	24	7	6	29	116	242	10	56	53	40	0	
null	294	206	238	324	323	134	151	152	129	42	400	168	214	211	198	158	0

Note: The first number of the treatment triad references gamma level, the second purity level, and the third color temperature level. A value of 1 refers to the lowest level (-a) and 5 to the highest level (+a). For example, the treatment 242 refers to the condition where gamma is set to -1, purity to +1, and color temperature to -1. See Table 15.for a complete mapping of the present coding scheme to the 15 treatment conditions.

TABLE 31: SUM OF RANKS MULTIPLE COMPARISONS FOR THIRD-PARTY HARDCOPY PREFERENCE RANKINGS

Treatment		224	222	244	242	424	422	444	442	533	133	353	313	335	331	333	null
	Sum of Ranks	572	529	583	558	367	312	343	377	363	770	483	453	434	501	388	311
224	572	0															
222	529	43	0														
244	583	11	54	0													
242	558	14	29	25	0												
424	367	205	162	216	191	0											
422	312	260	217	271	246	55	0										
444	343	229	186	240	215	24	31	0									
442	377	195	152	206	181	10	65	34	0								
533	363	209	166	220	195	4	51	20	14	0							
133	770	198	241	187	212	403	458	427	393	407	0						
353	483	89	46	100	75	116	171	140	106	120	287	0					
313	453	119	76	130	105	86	141	110	76	90	317	30	0				
335	434	138	95	149	124	67	122	91	57	71	336	49	19	0			
331	501	71	28	82	57	134	189	158	124	138	269	18	48	67	0		
333	388	184	141	195	170	21	76	45	11	25	382	95	65	46	113	0	
null	311	261	218	272	247	56	1	32	66	52	459	172	142	123	190	77	0

Note: The first number of the treatment triad references gamma level, the second purity level, and the third color temperature level. A value of 1 refers to the lowest level (-a) and 5 to the highest level (+a). For example, the treatment 242 refers to the condition where gamma is set to -1, purity to +1, and color temperature to -1. See Table 15.for a complete mapping of the present coding scheme to the 15 treatment conditions.

Hardcopy Acceptance Ratings

A frequency count was taken of the number of prints deemed unacceptable within each treatment condition. A rejection proportion then was calculated as: RP = (the number of prints

rejected / the number of prints observed). Rejection proportions were separated by party and then averaged across participant and scene. Factor levels were represented in coded units and analyzed using a quadratic response-surface regression.

First-party analysis revealed a significant effect for gamma alone. Gamma, gamma^2, and color temperature were statistically significant for third-party photographs (Tables 32 and 33). For both first- and third-party datasets, higher rejection rates occurred at lower gamma levels. Finally, third-party rejection rates varied by color temperature as well, with lower rejection rates at lower color temperatures.

These results indicate that participants accepted more photographs when the photos had received minimal editing. The higher rejection rates at lower gamma levels may be attributed to the fact that contrast was adjusted to a greater degree when apparent contrast was low. Consequently, the digital values of the images were substantially altered, resulting in a print with objectionable degradation.

The pattern of rejection rates for third-party photographs, across color temperature, supports the indication of participant preference for blue-cyan print biases that was present for hardcopy color quality ratings.

TABLE 32: FIRST-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR HARDCOPY REJECTION RATES (MSE = 0.01 R^2 = 0.79)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.2362463	0.118319	2.00	0.1166
gamma	-0.09853	0.027236	-3.62	0.0224
purity	0.0048169	0.027236	0.18	0.8682
temp	0.0036984	0.027236	0.14	0.8985
gamma*gamma	0.0307108	0.041154	0.75	0.4970
purity*gamma	0.0075	0.037296	0.20	0.8504
purity*purity	-0.000712	0.041154	-0.02	0.9870
temp*gamma	-0.0225	0.037296	-0.60	0.5789
temp*purity	7.35e-15	0.037296	0.00	1.0000
temp*temp	0.0050012	0.041154	0.12	0.9091
block[1-2]	-0.006246	0.031853	-0.20	0.8541

TABLE 33: THIRD-PARTY RESPONSE SURFACE REGRESSION RESULTS FOR HARDCOPY REJECTION RATES (MSE = 0.002 R^2 = 0.98)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.3123896	0.048485	6.44	0.0030
gamma	-0.136355	0.011161	-12.22	0.0003
purity	0.0219981	0.011161	1.97	0.1200
temp	0.0329652	0.011161	2.95	0.0418
gamma*gamma	0.0500539	0.016864	2.97	0.0412
purity*gamma	-0.00125	0.015283	-0.08	0.9387
purity*purity	-0.001365	0.016864	-0.08	0.9394
temp*gamma	0.00625	0.015283	0.41	0.7035
temp*purity	-0.00875	0.015283	-0.57	0.5976
temp*temp	0.0100613	0.016864	0.60	0.5829
block[1-2]	-0.02239	0.013053	-1.72	0.1614

Discussion

Results have indicated that monitor calibration did influence perceived softcopy color quality, softcopy editing behavior, and subsequent perceived hardcopy color quality. Perception of softcopy CQ ratings was determined predominantly by the CRT gamma level. Gamma also dominated editing behavior, where color temperature played a minor role and was limited primarily to third-party photos. The relation between excitation purity and editing behavior was negligible. Edits made in response to gamma, and to a lesser degree color temperature, were of great enough magnitude to negatively impact perceived hardcopy CQ. Of all the independent variables, gamma demonstrated the largest impact on hardcopy CQ ratings, preferences, and predicted hardcopy rejection rates.

Block

The blocking factor was statistically significant for brightness edits, contrast edits, and hardcopy CQ ratings. Meaning, participants' editing behavior varied between the two softcopy editing sessions in turn, influencing hardcopy CQ ratings. However, the magnitude of difference between blocks was minimal. The delta mean values among brightness edits fell below 5 units. Similarly, the difference between mean contrast edits for block 1 and block 2 was a borderline value of 5.02. Yet, the delta of 5 units was most likely the source of the associated difference between hardcopy CQ ratings for block 1 and block 2. Here, block 1 (145.9) received a higher average CQ rating than block 2 (141.2). And it was block 1 (20.4) that received a lower average contrast increase over block 2 (25.4). Hence, the block 2 photographs would have had more degradation than the block 1 photos, justifying a lower CQ rating.

With respect to CQ ratings though, a delta of 10 units between factor levels represents only a 5% difference relative to the modulus of 200. For example, a rating of 150 meant the image was deemed 25% worse than the modulus image. A photo rated 160 was deemed 20% worse. Thus, the difference between ratings of 150 and 160, relative to the modulus, is only 5%. A delta of 20 units equates to a difference of 10% and may be considered a more meaningful difference given the subjective nature of the rating scale.

Though an effect for block seemed apparent, the magnitude of differences, both for edits and ratings, were quite small and may be deemed insignificant for practical applications. Depending on scene content and edit dimension, a change of five units (the smallest change allowed by the color tool) could go undetected by the user. Though not substantiated via measurement, this observation indicates a five unit change may lie near visual detection threshold. Thus, a difference in edit behavior of five units or less is not likely to meaningfully impact the users' behavior at the time of editing. Given that a difference of five edit units

carried over to a difference in perceived CQ that fell well below 5%, edit differences of five units or less also are unlikely to meaningfully influence subsequent perceptions of photographic prints.

Gamma

Increases in CRT gamma level were associated with increases in softcopy color quality ratings. Given a display gamma of 1.0[5], photographs rendered on the CRT appeared washed-out with poor color saturation. Indeed, this was the gamma level that elicited the lowest CQ ratings (Figure 17). With increasing gamma, on-screen photographs took on a more saturated, high contrast, and crisp appearance. As CRT gamma increased so did the CQ ratings provided by the participants. However, the relationship between CQ and gamma was not a linear one. The fastest gain in CQ was achieved between gamma values of 1.0 and 2.0. Above 2.0, the increase in CQ resulting from further increases in display gamma was minor.

Participants compensated for gamma effects by adjusting brightness and contrast dimensions (Figure 20). Predicted brightness edits increased with increasing gamma. Contrast edits were of a much greater magnitude and, unlike brightness, increased with decreasing gamma. At the higher gamma levels, consistent contrast additions were predicted. Changes to contrast rose dramatically though, as gamma was reduced from 2.0 to 1.0. The fact that contrast edits were predicted at all levels of gamma, as well as all levels of purity and color temperature, indicates participants had a general preference for softcopy photos with higher apparent contrast (Figures 20-22).

Contrast boosting at low gamma levels was so extreme that many of the printed photographs suffered from pervasive clipping. This caused extensive loss of saturation and detail in the photographs, degrading them to the point where both hardcopy CQ and rejection rates were negatively impacted. Color quality ratings were much lower for prints generated under low gamma levels than for those edited under high gamma levels (Figure 18). Furthermore, the image degradation caused by editing at gamma levels of 0 (2.0) and below led to substantially higher rejection rates (Figure 19).

Hardcopy CQ preferences also were influenced by CRT gamma levels. Sorting treatments by descending sum-of-ranks values produced a remarkable trend for gamma (Figure 23). Participants clearly preferred the prints generated under high gamma levels (i.e., treatment 533). Color quality preferences declined as gamma was reduced from 3.0 (533) to 1.0 (133).

[5] For the remainder of the discussion section, factor levels will be referred to using natural values. However, it should be noted that all analyses were conducted using coded values. Had analyses been conducted using natural values, results may vary slightly from those presented.

Color Temperature

Participants' CQ ratings for their own photographs were relatively stable across the range of color temperature tested, though a slight trend was present. The CQ of third-party photographs on the other hand, was deemed superior at higher color temperatures.

Color temperature did influence editing along red, blue, and green dimensions. Consistent with softcopy rating patterns, edits along red and blue dimensions were of smaller magnitude at higher color temperatures. Blue edits increased as color temperature declined. At the same time, red was increasingly subtracted as color temperature approached 4061 K. The overall effect was to shift warmer color balances to a cooler appearance. These editing patterns were present for both first- and third-party data, though to a much smaller degree for the former.

Color temperature also had a statistically significant effect on green editing behavior. However, both mean and predicted values demonstrated the effect to be of such low magnitude (i.e., < 5) it was inconsequential (Figure 22).

Given that color temperature induced only minor changes to color balance for first-party photos, subsequent predicted hardcopy CQ ratings were consistent across all color temperature levels (Figure 18). Rejection rates too were low, falling just above 20% across all color temperatures (Figure 19). Third-party CQ ratings were expected to be lower at the lower color temperature because of a larger change in color balance at this level. This was not the case. Hardcopy CQ ratings were highest at the lowest color temperature, declining as color temperature increased. Rejection rates for third-party photos followed suit, increasing with increased color temperature. This indicates participants may have had either, a preference or an increased tolerance for, photographs with cool color biases. Newhall, Van Wie, and Colton (1955) examined color balance preferences of individuals in Rochester, NY, for 35mm film projections of natural scenes. They found cyan biases were preferred over red, green over magenta, and blue over yellow. This pattern yields an overall preference toward cooler color balances. In addition, the acceptance contours for the biased photographs extended further into the cooler dimensions than they did into red or magenta dimensions, indicating an increased tolerance for cooler color balances.

It is worth noting that color temperatures as low as 4000 K, and to a lesser extent 6500 K, are likely to be rare in the home environment. However, the choice of factor levels in this study was dictated by the alpha criterion employed for the CCD (i.e., 1.871). Over the range of color temperatures most likely to be encountered in home computing environments, 9300 K to 14539 K, the CQ ratings for softcopy and hardcopy photos were quite similar. The differences between predicted CQ ratings over these temperature levels did not represent levels of practical

significance. However, with respect to third-party photos alone, rejection rates over this range still maintained a difference of more than 10%.

Three interactions involving color temperature were statistically significant. First, green editing behavior systematically varied across the range of color temperatures depending upon both the level of excitation purity and the level of gamma (Figure 24). In each case, the range of the interaction fell below the 5-unit criterion for practical significance. However, the third interaction is worthy of discussion. Brightness edits varied over the range of color temperatures, depending on the level of purity (Figure 25). When purity was 0, brightness edits were fairly consistent about a value of 10. For purities below the BBC, brightness increased with increasing color temperature. When purities lay above the BBC, the opposite effect was obtained; brightness decreased with increasing color temperature. This would seem to suggest that at low color temperatures, biases in the green direction are perceived dimmer than biases in the magenta direction, while the reverse is observed at higher color temperatures.

Excitation Purity

The main effect of excitation purity was minimal and limited to red editing behavior. As purity moved from below the BBC to above the curve, more red was added to first-party photographs. No similar trend was observed for third-party photos. Three of the five color temperatures included in this study were located toward the blue region of the color temperature spectrum. So purity levels of 0 (0), 1.0 (6), and 1.871 (12) would have driven the color balance toward cyan creating an even cooler appearance to on-screen photographs. If participants perceived this cyan shift, and found it objectionable, they could be expected to compensate by decreasing cyan (equivalently increasing red). Indeed, this was the trend observed in the data. However, the effect was quite small, with a difference of only 4.4 predicted units between purity levels below the curve and those above the BBC.

First-Party vs Third-Party Photos

Average color adjustments to first-party photographs were minimal. Participants concentrated their editing efforts along the brightness and contrast dimensions, for their own photographs, leaving red, green, and blue dimensions relatively unaltered. This was true across all levels of gamma, purity, and color temperature, indicating that participants' photographs may have had inherent attributes that solicited this behavior (i.e., many flash scenes).

With respect to third-party photographs, participants focused their efforts on contrast, red, and blue dimensions. The brightness and green dimensions were edited fairly consistently across all treatments. Contrast edits were primarily driven by gamma level, where red and blue adjustments were driven by color temperature. Though blue additions were predicted across all

levels of gamma, purity and color temperature, variability in blue adjustments was only found across color temperature. This pattern of editing behavior indicated participants were more sensitive to the influences of color temperature when viewing third-party photographs. Consequently, both gamma and color temperature played significant roles in the prediction of CQ and rejection rates.

It is interesting to note the relationship of first-and third-party CQ ratings throughout the course of the study. Predicted softcopy ratings were higher for third-party photographs, indicating participants initially felt the CQ of these photos was superior to their own. Curiously enough though, it was the third-party photographs that received larger additions of blue, subtractions of red, and to a lesser extent, increases in contrast. Hence, third-party photos were digitally altered to a greater extent than first-party photographs. This differential in editing behavior led to a reversal in perceived color quality for hardcopy prints. For this medium, third-party predicted hardcopy CQ ratings were substantially lower than first-party photos. In turn, participants more often rejected the CQ of third-party photographs relative to their own.

Another interesting observation may be made for first-party CQ ratings. In almost every case, predicted hardcopy CQ ratings exceeded initial softcopy CQ ratings for the participants own photographs. The opposite trend was found for third-party photographs: predicted hardcopy CQ always fell below the initial softcopy ratings. Editing results show that participants substantially increased both contrast and brightness for their own photos, to an extent where color quality should have been negatively impacted. Yet hardcopy CQ generally exceeded softcopy CQ.

These observations indicate that participants may be using different rules for quality assessment depending on whether or not they have a personal involvement with a photograph. Weiman, Sayer, and Brunetti (1993) investigated the basis of personal evaluations of image quality for first- and third-party photographs. Their findings indicated that individuals used aesthetic or emotional criteria more than technical criteria for evaluating their own photographs. Quality ratings of photographs taken by strangers were based more on technical merit than aesthetic/emotional merit. Use of different criteria for judging personal and nonpersonal photographs leads to different perceived quality ratings. Zwick (1978) found that pictures quality ratings were higher when individuals had a personal involvement with the subject matter depicted in the photographs. If participants felt the subject matter was important to them or if it brought about pleasant memories for the original event, then a higher rating would be provided than justified by technical merit alone (Faulkner and Segur, 1984). Yet the individuals who were lenient with their own photographs, could rate the photos of third-parties just as

FIGURE 17: EMPIRICAL SOFTCOPY CQ RATINGS BY GAMMA, PURITY, AND COLOR TEMPERATURE

Y axis: predicted rating
X axis: factor level
Bars: 1st-party data
Line: 3rd-party data

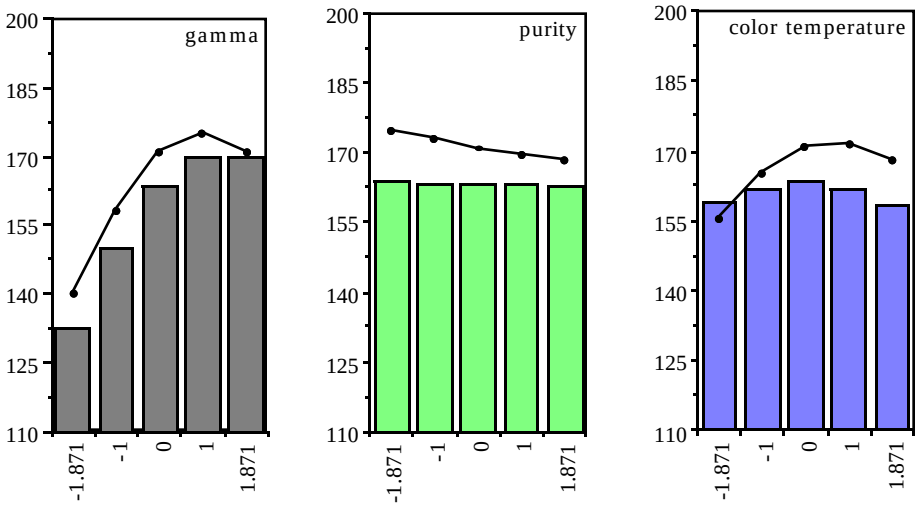


FIGURE 18: EMPIRICAL HARDCOPY CQ RATINGS. BY GAMMA, PURITY, AND COLOR TEMPERATURE

Y axis: predicted rating
X axis: factor level
Bars: 1st-party data
Line: 3rd-party data

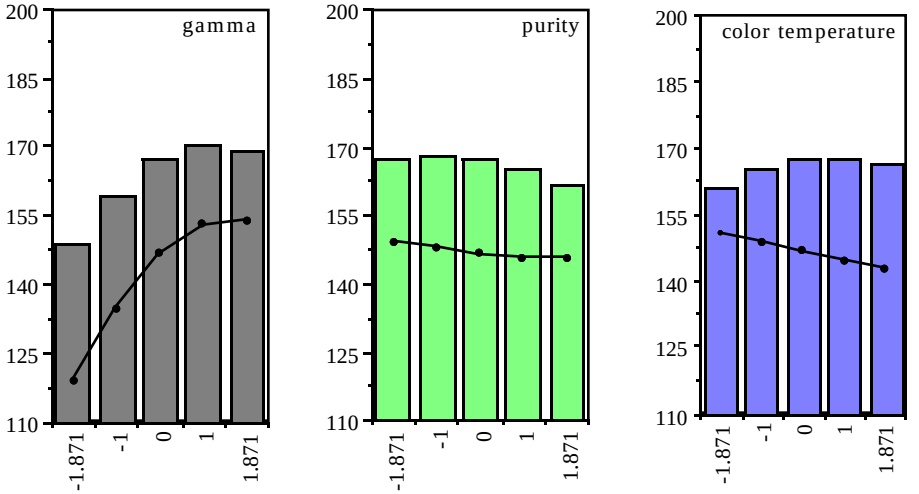


FIGURE 19: EMPIRICAL REJECTION PROPORTIONS BY GAMMA, PURITY, AND COLOR TEMPERATURE

Y axis: predicted percent rejection
X axis: factor level
Bars: 1st-party data
Line: 3rd-party data

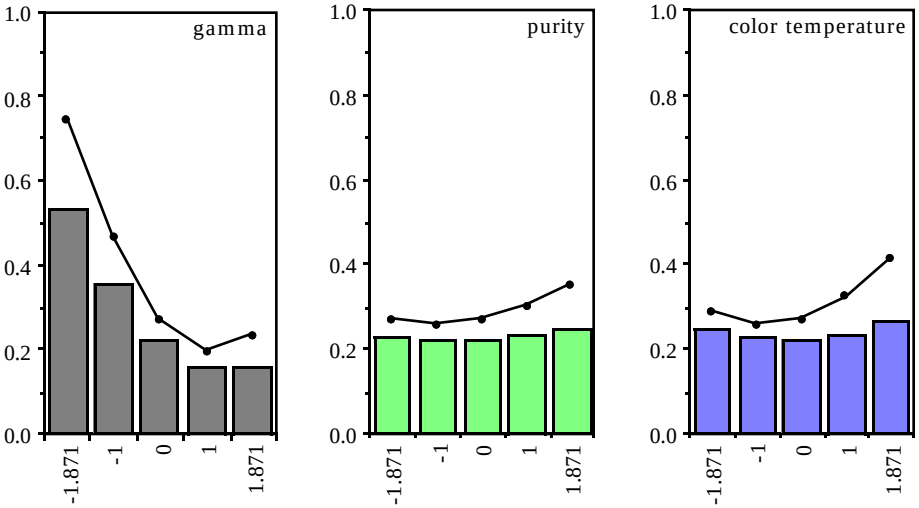


FIGURE 20: EMPIRICAL EDITS BY GAMMA

Y axis: predicted edit
X axis: factor level
Red Bars: red edits
Green Bars: green edits
Blue Bars: blue edits
Gray Bars: brightness edits
Black Bars: contrast edits

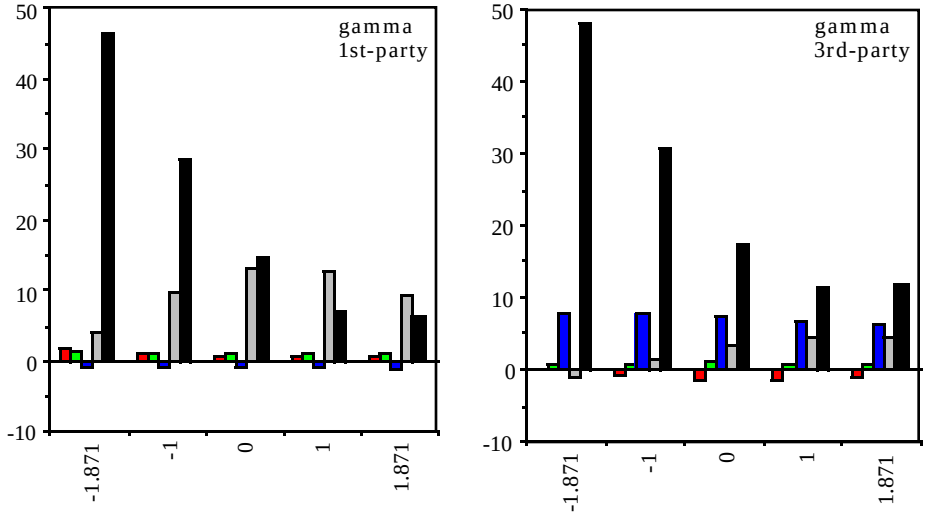


FIGURE 21: EMPIRICAL EDITS BY PURITY

Y axis: predicted edit
X axis: factor level
Red Bars: red edits
Green Bars: green edits
Blue Bars: blue edits
Gray Bars: brightness edits
Black Bars: contrast edits

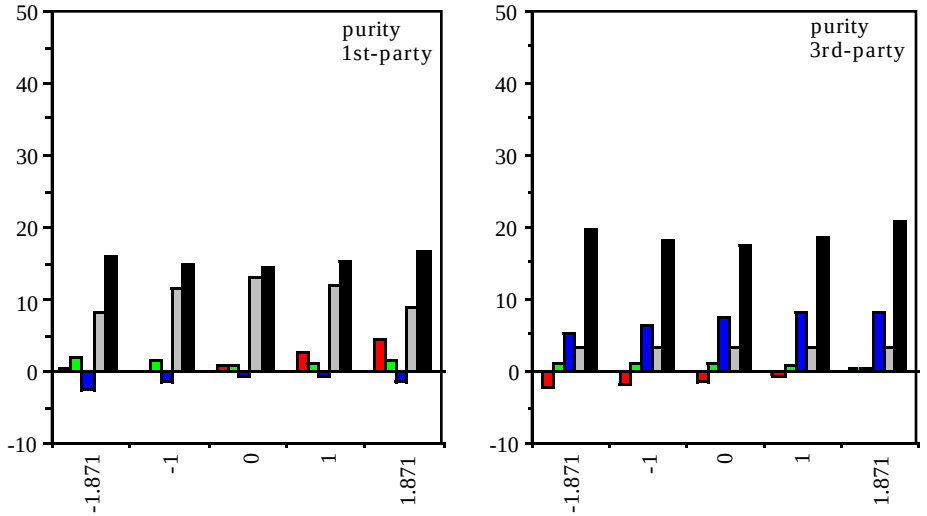


FIGURE 22: EMPIRICAL EDITS BY COLOR TEMPERATURE

Y axis: predicted edit
X axis: factor level
Red Bars: red edits
Green Bars: green edits
Blue Bars: blue edits
Gray Bars: brightness edits
Black Bars: contrast edits

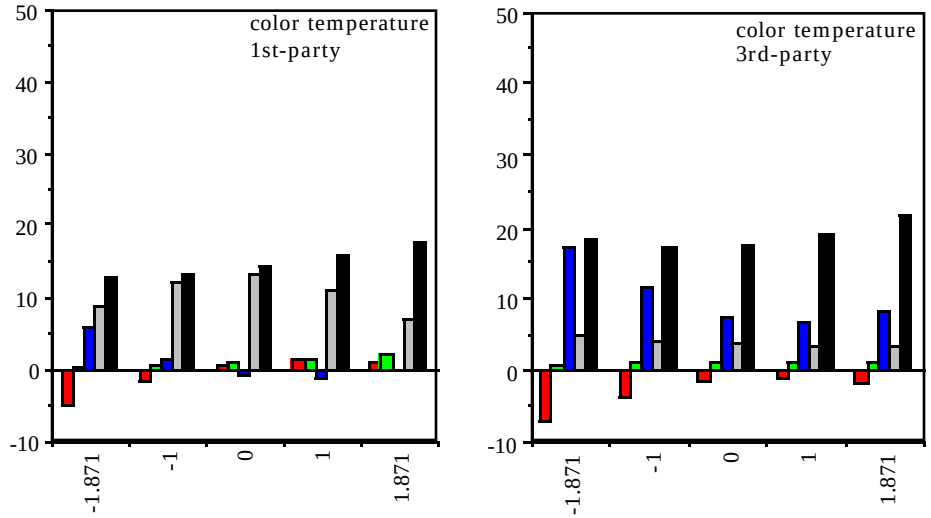


FIGURE 23: HARDCOPY CQ PREFERENCES

Y axis: sum of ranks
X axis: treatment
Bars: 1st-party data
Line: 3rd-party data

Note: the first digit in each treatment label refers to gamma, the second to purity, and the third to color temperature. A value of 1 indicates the lowest factor level, 5 the highest factor level. For example, the label 133 references the treatment where gamma = -1.871, purity = 0, and color temperature = 0. (See Table 15.)

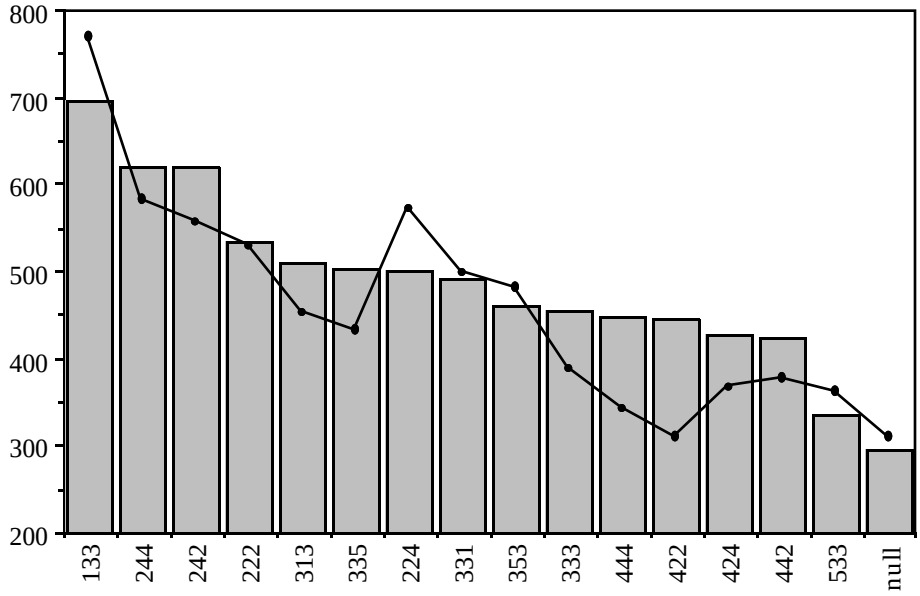


FIGURE 24: COLOR TEMPERATURE INTERACTIONS FOR GREEN EDITS

Y axis: predicted green edit
X axis: color temperature level

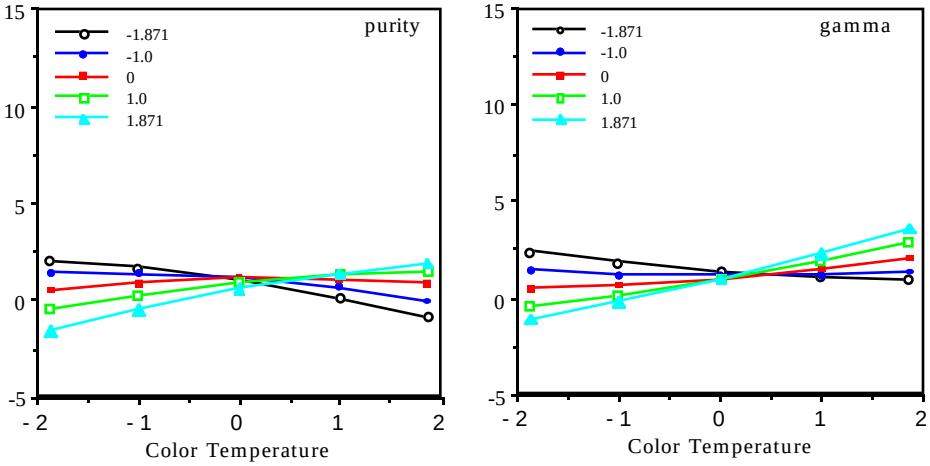
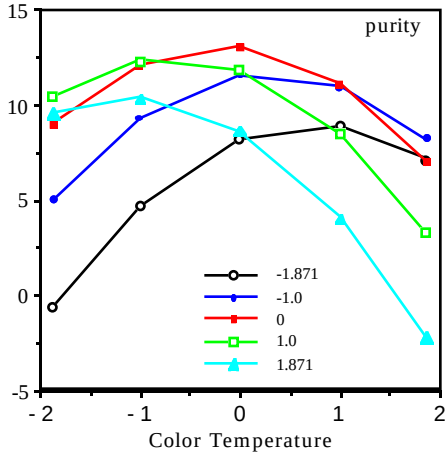


FIGURE 25: COLOR TEMPERATURE INTERACTION FOR BRIGHTNESS EDITS

Y axis: predicted brightness edit
X axis: color temperature level



critically as expert judges who only based their ratings on technical merit (Faulkner and Segur, 1984). Data from the present study would indicate that personal photographs were given more tolerance, perhaps due to aesthetic/emotional criteria, than third-party photographs.

Null Photographs

An additional observation may be made regarding participants' CQ preferences. The sum-of-ranks value for the null photographs were smaller than that of any experimental treatment. This indicates participants rated the null photographs as most preferred more frequently than any other photograph, a result that supports the assumption that a pleasing, good quality photograph would be achieved by simply passing it through the system unedited. Furthermore, average rejection rates for both first-party (18%, SE=0.0) and third-party (18%, SE=0.07) null photos were superior to a majority of those generated under the experimental treatments (Figure 23).

Conclusions

This study investigated the relation between CRT color balance and perceived color quality for softcopy and hardcopy photographs generated in a home DCI system. The effect of excitation purity on perceived softcopy color quality, softcopy editing behavior, and subsequent perceived hardcopy color quality was negligible. The role of color temperature was more complex, carrying much greater influence with third-party photographs than with first-party photographs. At lower color temperatures, perception of color quality was reduced. This carried over to an editing behavior that led to additions of both blue and cyan. At warmer color temperatures the additions were of greater magnitude than for cooler temperatures. Yet the additions across the board indicated a preference for cooler on-screen color balances. This preference for cooler photos carried over to the hardcopy ratings. Hardcopy color quality was perceived higher for the photographs generated under more extreme editing. Rejection rates followed suit, showing lower rates at lower color temperatures.

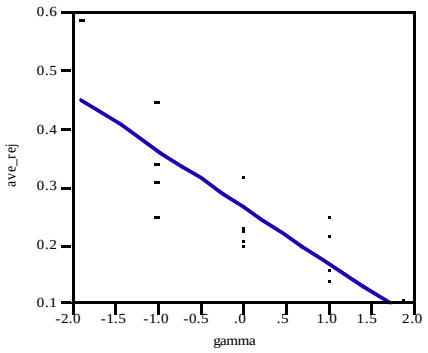
However, it was CRT gamma that predominantly determined how the color quality of photographs was perceived by users. In addition, gamma substantially influenced the editing behavior of photographs viewed on the CRT. Contrast additions were increased when gamma levels were low. Though this behavior generated more appealing on-screen photographs, it significantly altered the digital values of the photographs. Consequently, the printed photos had severe degradation that negatively impacted their perceived color quality. In turn, hardcopy rejection rates were higher for prints generated under low gamma levels.

With respect to hardcopy rejection rates, the dominance of gamma may be supported by prediction models containing gamma alone. A prediction model of first-party rejection rates based on a linear relation with gamma alone accounts for nearly 70% of the variance in the data (Figure 26). The complete CCD quadratic model accounted for only an additional 10% of the variance. The remainder of the noise in the data can most likely be attributed to personal involvement with the subject matter, including its importance to the user and the nature of the memories it elicits.

Because users seemed to base their evaluations of third-party photographs on technical merit to a much greater degree than for first-party photos, a larger portion of data variance may be accounted for by prediction models. The complete CCD quadratic model relating CRT characteristics to third-party rejection rates accounts for 98% of the variation. Reducing the model to three parameters, gamma, gamma^2, and color temperature, trades off a mere 5% of variance accountability. Finally, to emphasize the significance of gamma, a quadratic model based on gamma alone accounts for 88% of data variance (Figure 26).

FIGURE 26: HARDCOPY REJECTION RATE PREDICTION MODELS BASED ON GAMMA ALONE

First-Party



Linear Fit

ave_rej = 0.27 – 0.09853 gamma

Summary of Fit

RSquare	0.687609
RSquare Adj	0.663579
Root Mean Square Error	0.071341
Mean of Response	0.27
Observations (or Sum Wgts)	15

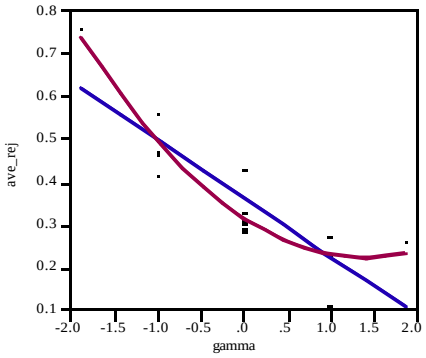
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	0.14563559	0.145636	28.6145
Error	13	0.06616441	0.005090	**Prob>F**
C Total	14	0.21180000		0.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.27	0.01842	14.66	<.0001
gamma	-0.09853	0.018419	-5.35	0.0001

Third-Party



Polynomial Fit degree=2

ave_rej = 0.31753 – 0.13636 gamma + 0.04914 gamma^2

Summary of Fit

RSquare	0.884467
RSquare Adj	0.865212
Root Mean Square Error	0.059128
Mean of Response	0.366667
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.32117962	0.160590	45.9334
Error	12	0.04195372	0.003496	**Prob>F**
C Total	14	0.36313333		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.3175271	0.020804	15.26	<.0001
gamma	-0.136355	0.015266	-8.93	<.0001
gamma^2	0.0491354	0.014132	3.48	0.0046

Recommendations

If consumers choose to generate hard-copy prints from edited soft-copy images, the output will reflect any image manipulation they have undertaken. When the CRT is used as a preview device for a printer, as it is in the DCI system described herein, consumers are likely to expect the printed photos to match the appearance of the CRT "originals" (or their memory of the CRT originals). This may be particularly true when image manipulation has occurred. If manipulation was extensive, what the consumer receives in terms of printed output will appear quite different from the soft-copy version and, thus, may be deemed unacceptable.

This research shows, that image manipulation levels may indeed be extensive enough to induce edit magnitudes that negatively impact perceived color quality of prints. Moreover, these findings pertain to CRT calibrations that are likely to be found in consumer marketplaces. The primary concern then, lies with user acceptance of remote printing services, given the potential for unacceptable system output. Remote print service providers run the risk of an unacceptably high volume of requests for reprints or refunds for their services, and possibly erosion of their customer base.

Given that CRT gamma is a dominant factor, the development of solutions for DCI system soft-copy to hard-copy matching issues should initially focus on gamma. Possible solutions may include the development of monitor characterization tools that guide users through a series of visual stimuli designed to determine the gamma level of the CRT. This information could be packaged with the image and used by the print service provider for image quality optimization. Efforts in this direction have been undertaken at Kodak (Lee and Daly, 1995; Oliyide, Daly, and Lee, 1994) and other companies that currently have products available on the market (e.g., Sonnetech's Colorific). However, these programs need to be validated under the spectrum of viewing conditions present in home environments. In addition, a means for attaching the characterization data to an on-line order would need to be developed.

An alternative solution may include the development of color quality optimization algorithms to be implemented by the print service provider. In this scenario, the remote printer may adopt a policy of ignoring the condition of all incoming orders, in favor of simply printing the best possible photograph. In conjunction with this approach, a consumer awareness program may be undertaken, by print service providers, imaging software companies, computer companies, and monitor manufacturers, to educate users about the complexities of DCI system interactions. The goal of such a campaign would be to dissuade users from making significant edits to images that will be submitted for remote printing.

Both of these scenarios require users to take responsibility for the shortcomings of the DCI system. The monitor characterization scenario would require users to repeat the characterization procedure each time viewing conditions and/or users changed. It is unlikely that users will be vigilant in updating this information and, thus, will not reap the benefits of the procedure. The optimization scenario may alienate high-end users who have well-calibrated DCI systems and who wish to alter the color balance of their images to achieve a particular effect. In each case, the potential for consumer dissatisfaction remains.

The best approach from the users' perspective would be the development of smart DCI systems that automatically measure system characterization and seamlessly handle any adjustments during image processing. Smart DCI systems enable monitor self-calibration and communication of the results to image manipulation programs. These programs, in turn, may use the calibration data for one of two purposes: either to adjust the edits made by users or to adjust the apparent contrast of images presented during manipulation.

This approach benefits from the fact that the user is absolved of responsibility for DCI system complexity. Smart DCI systems enable users to see on their monitors a reasonable and pleasing facsimile of what they will see on their prints.

Until this level of technology is achieved, Internet-based print service providers may wish to generate the best quality photograph possible, regardless of the balance of the print at the time of submittal. To accomplish this, automatic balancing algorithms or improved procedures for manual balancing may need to be developed.

REFERENCES

American Society for Testing and Materials (1996). ASTM standards on color and appearance measurement (5th Ed). Philadelphia, PA: ASTM. pp. 237-248.

Berger, R.W. (1997). Why do images appear darker on some displays? An explanation of monitor gamma. [On-Line]. Available: http://www.cs.cmu.edu/afs/cs.cmu.edu/user/rwb/www/gamma.html

Berns, R.S. and Choh, H-K. (1995). Cathode-Ray tube to reflection-print matching under mixed chromatic adaptation using RLAB. *Journal of Electronic Imaging*, 4(4), 347-359.

Berns, R.S., Motta, R.J., and Gorzynski, M.E. (1993). CRT Colorimetery part I: Theory and practice. *Color research and Application*, 18(5), 299-314.

Brainard, D.H. and Ishigami, K. (1995). Factors influencing the appearance of CRT colors. In Proceedings of the third Imaging Science and Technology/Society for Information Display (IS&T/SID) Color Imaging Conference (pp. 62-66). Scottsdale, Arizona: IS&T/SID.

Breneman, Edwin, J. (1977). Perceived saturation in complex stimuli viewed in light and dark surrounds. *Journal of the Optical Society of America*, 67(5), 657-662.

Breneman, E.J. and Witzel, R.F. (1962). The effects of color temperature on apparent screen brightness. Rochester, NY: Eastman Kodak Company.

Brill, M.H. and Derefeldt, G. (1991). Comparison of reference-white standards for video display units. *Color Research and Application*, 16(1), 26-30.

Burnham, R.W., Evans, R.M., and Newhall, S.M. (1957). Prediction of color appearance with different adaptation illuminations. *Journal of the Optical Society of America*, 4791), 35-42.

Burnham, R. W., Hanes, R.M. & Bartleson, C.J. (1963). Color: A guide to basic facts and concepts. New York: John Wiley & Sons. pp 179-187.

CIE (1986). Colorimetery, 2nd Edition. (Publication 15.2). Paris: Central Bureau of the CIE.

Collins, Douglas (1990). The story of Kodak. New York: H.N. Abrams.

Cottone, P. (1996). Unpublished report. Eastman Kodak Company.

Cottone, P. and Miller, M.E. (1997). Unpublished results. Eastman Kodak Company.

Díaz, J.A., Jiménez, J.R., Hita, E., and Jiménez del Barco, L. (1996). Optimizing the constant-channel chromaticity and color gamut of CRT displays by control of brightness and contrast levels. *Applied Optics*, 35(10), 1711-1718.

Engen, T. (1971). Psychophysics II: Scaling methods. In Kling, J. and Riggs, L. (Eds) Woodworth and Schlosberg's Experimental Psychology. (3rd Ed). London: Metheun & Co., LTD.

Fairchild, M.D (1991). Formulation and testing of an incomplete-chromatic-adaptation model. *Color Research and Application*, 16(3), 243-250.

Fairchild, M.D. (1993). Chromatic adaptation in hard-copy / soft-copy comparisons. In Bares, J. (Ed), Proceedings of the International Society for Optical Engineering (SPIE): Vol. 1912: Color hard copy and graphic arts II (pp. 47-61). San Jose, CA: SPIE.

Fairchild, M.D (1995). Considering the surround in device-independent color imaging. *Color Research and Application*, 20(6), 352-363.

Fairchild, M.D. (1998). Color appearance models. Reading, MA: Addison Wesley Longman, Inc.

Fairchild, M.D. and Reniff, L. (1995). Time course of chromatic adaptation for color-appearance judgments. *Journal of the Optical Society of America A*, 12(5), 824-833.

Faulkner, T.W. and Segur, R.K. (1984). Unpublished report. Eastman Kodak Company.

Giorgianni, E.J. and Madden, T.E. (1997). Digital color management encoding solutions. Reading, MA: Addison-Wesley.

Gorzynski, M. and Berns, R.S. (1990). The effects of ambient illumination and image color balance on the perception of neutral in hybrid image display systems. In Proceedings of the International Society for Optical Engineering (SPIE): Vol. 1250: Perceiving, measuring, and using color (pp. 111-118). San Jose, CA: SPIE.

Hunt, R.W.G. (1977a). The specification of colour appearance I. Concepts and terms. *Color Research and Application*, 2(2), 55-68.

Hunt, R.W.G. (1977b). The specification of colour appearance II. Effects of changes in viewing conditions. *Color Research and Application*, 2(3), 109-120.

Hunt, R.W.G. (1980). Chromatic adaptation in image reproduction. Rochester, NY: Eastman Kodak Company.

Hunt, R.W.G. (1995). The reproduction of colour. Fifth edition. Kingston-upon-Thames, England: Fountain Press.

Hunt, R.W.G. (1996). Viewing parameters affecting self-luminous, reflection and transmissive colours. *Displays*, 16(4), 157-162.

Hurvich, L.M. (1981). Color Vision. Sunderland, MA: Sinauer Associates Inc.

Kaiser, P.K. and Boynton, R.M. (1996). Human color vision. Second edition. Washington, DC: Optical Society of America.

Katoh, N. (1994). Practical method for appearance match between softcopy and Hardcopy. In Walowit, E. (Ed), Proceedings of the International Society for Optical Engineering (SPIE): Vol. 2170: Device-independent color imaging (pp. 170-181). San Jose, CA: SPIE.

Keller, P.A. (1996). Basics of color display specification. *Information Display*, 1, 18-22.

Kuehni, R.G. (1997). Color an introduction to practice and principles. Chapter 10. NY: John Wiley and Sons, Inc..

Kuehni, R.G. (1989). What is color? A speculative essay. *Color Research and Application*, 14(4), 207-210.

Kuehni, R.G. (1981). What the educated person knew about color A.D. 1700. *Color Research and Application*, 6(4), 228-232.

Land, E.H. (1977). The Retinex theory of color vision. *Scientific American*, 237(6), 108-128.

Lang, H. (1983). Trichromatic theories before Young. *Color Research and Application*, 8(4), 221-231.

Lee, H.C. and Daly, S. (1995). Unpublished report. Eastman Kodak Company.

Luo, M.R., Gao, X.W., and Scrivener, S.A.R. (1995). Quantifying color appearance. Part V. Simultaneous contrast. *Color Research and Application*, 20(1), 18-28.

McCann, J.J. (1973). Human color perception. In Eynard, Raymond (Ed) Color: Theory and imaging systems. Washington, DC: Society of Photographic Scientists and Engineers (SPSE). pp. 1-23.

McManus, Paul (1989). Color matching from video to hardcopy. *Proceedings of the Tenth Annual NCGA Conference and Exposition*, Vol. 1, 376-380.

Montgomery, G. (1988). Color perception: Seeing with the brain. *Discover*, 9(12), 52-59.

Myers, R.H. and Montgomery, D.C. (1995). Response surface methodology: Process and product optimization using designed experiments. New York: John Wiley & Sons, Inc.

Newhall, S.M., Van Wie, A.I., and Colton, E.K. (1955). Comparative color balance preferences in Bombay and Rochester. Unpublished report. Eastman Kodak Company.

Norman, Donald (1988). The psychology of everyday things. New York: Basic Books.

Oliyide, O., Daly, S. and Lee, H.C. (1994). Unpublished report. Eastman Kodak Company.

Patterson, R. (1994). Gamma correction and tone reproduction in scanned photographic images. *Society of Motion Picture and Television Engineers (SMPTE) Journal*, 103(6), 377-385.

Pitt, I.T. and Winter, L.M. (1974). Effect of surround on perceived saturation. *Journal of the Optical Society of America*, 64(10), 1328-1331.

Post, D.L. and Lloyd, C.J.C. (1994). Colour display gamuts and ambient illumination. *Displays*, 15(1), 39-43.

Poynton, C.A. (1993). "Gamma" and its disguises: The nonlinear mappings of intensity in perception, CRTs, film, and video. *Society of Motion Picture and Television Engineers (SMPTE) Journal*, 102(12), 1099-1108.

Siegel, S. and Castellan, N.J. (1988). Nonparametric statistics for the behavioral sciences. (2nd Ed.). New York: McGraw-Hill Book Company.

Tannas, L.E. (1992). Color in electronic displays. *Physics Today*, December, 52-57.

Vaughn, F. (1990). Color WYSIWYG comes of age. *Byte*, December, 275-279.

Ware, C. and Cowan, W.B. (1982). Changes in perceived color due to chromatic interactions. *Vision Research*, 22(11), 1353-1362.

Weiman, N., Sayer, J. and Brunetti, T. (1993). Unpublished report. Eastman Kodak Company.

Whitaker (1994). Electronic displays: Technology, design, and applications. New York: McGraw-Hill, Inc.

Wyszecki, G. (1986). Color Appearance. In Boff, K.R., Kaufman, L., and Thomas, J.P. (Eds), Handbook of perception and human performance. Volume I. New York: John Wiley & Sons.

Wyszecki, G. and Stiles, W. S. (1982). Color science: Concepts and methods, quantitative data and formulae. New York: John Wiley & Sons.

Zwick, D.M. (1978). Unpublished report. Eastman Kodak Company.

APPENDIX A

Reference Images

Figure A1: Boy Scene

Figure A2: Dog Scene

Figure A3: Stones Scene

Figure A4: Trio Scene

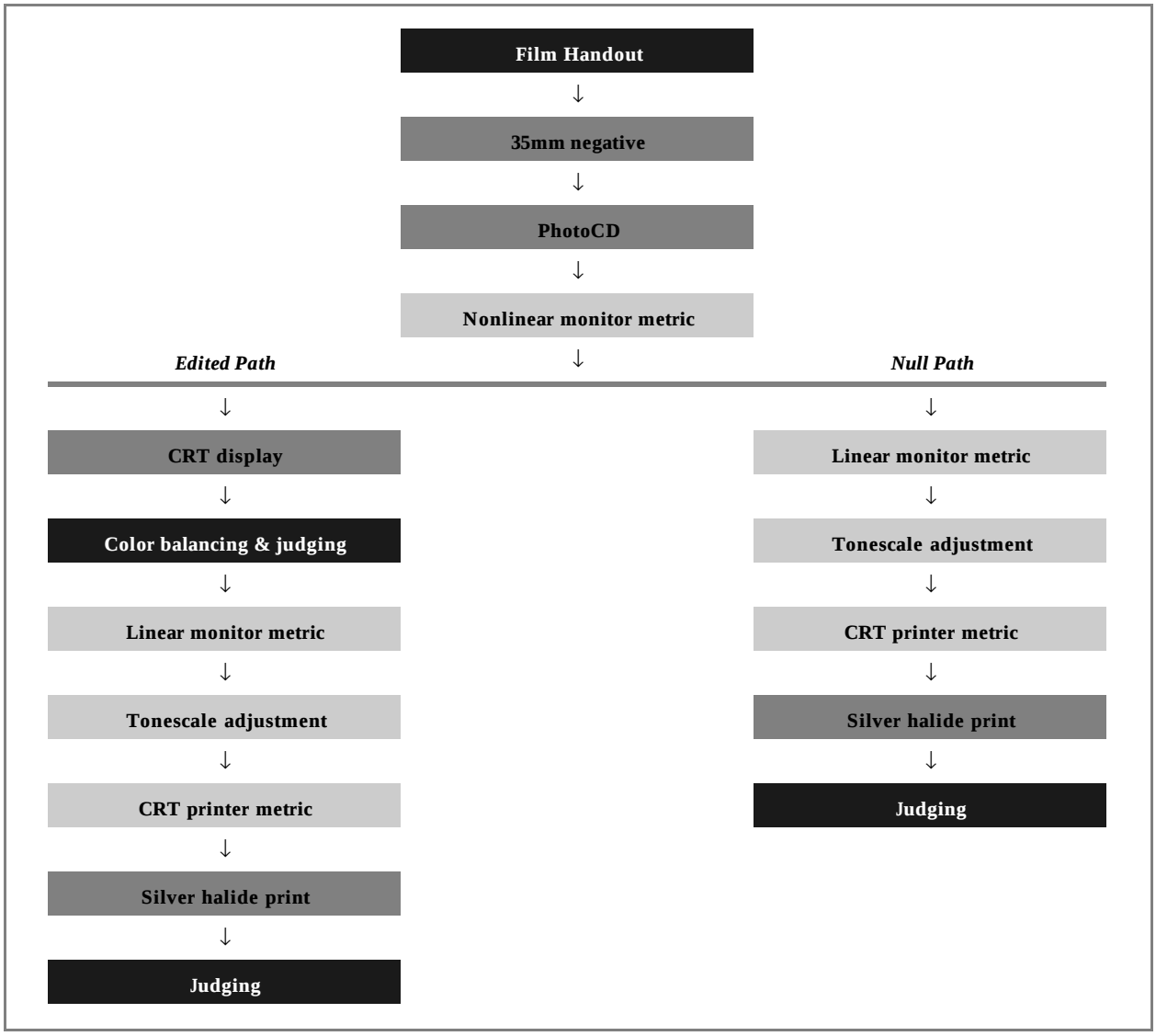
Figure A5: Snow Scene

Figure A6: Barn Scene

APPENDIX B

Image Processing Path

Figure B1: Image Processing Path



The following PPLUS script was used to transform images from PhotoCD format to monitor format, in preparation of the softcopy phase for both the pilot and primary studies. Models used within this script are presented below.

GENERATE_PIX

```
# Input Image Processing script for Wende Dewing
#
# Cathy Daniels / Wende Dewing
#
# Version 1.0 2/23/98
#
# Usage:
#   color_adjust_wende <in_image1> [<in_image2>...<in_imageN>]
#   [-o <outdir>] [-i <scene name>] [-vr]
#   where:
#     <in_imageX> Input photoCD image number.  This script assumes
#                 that any <in_imageX> 0 through 150 is a photoCD image number
#                 This script assumes the photoCD is mounted on the current
#                 system under /cdrom/cdrom0.
#     -o <outdir> Output directory where all temporary files and final images
#                 will be stored
#     -i <scene>  Image identifier to be used in filename
#     -v          Initial image as read from PhotoCD has
#                 a width that is smaller than the height
#     -r          rotate final image 90 degrees ccw
#
#     For help, use the -? flag, or use no arguments

#
# Initialize variables
#
set FILELIST = ""
set outdir = ""
set scene = ""
set version = "Version 1.0 1/6/98"
set vertical = "FALSE"
set rotate = "FALSE"
setenv SIL_DEF_FILE_FORMAT sil_imps
set image_size_model = /home/dewing/MODELS/image_down.mod
set thumb_size_model = /home/dewing/MODELS/newthumb_down.mod
set print_size_model = /home/dewing/MODELS/print_down.mod
set ycc_model = /home/dewing/MODELS/eds_shm2.mod
set res_set = "Base16 Base 16Base"
set size = "tmb sc hc"

#
# Parse the command line
#
set HAVE_FILE = "FALSE"
@ arg_count = 1
while( $arg_count <= $#argv )
  switch($argv[$arg_count])
    case -[oO]:
      @ arg_count++
      set outdir = $argv[$arg_count]
      breaksw
    case -[iI]:
      @ arg_count++
      set scene = $argv[$arg_count]
      breaksw
    case -[vV]:
      set vertical = "TRUE"
      breaksw
    case -[rR]:
      set rotate = "TRUE"
      breaksw
    case -[abdefghjklmnpqstuwzABDEFGHJKLMNPQSTUWZ]:
      echo "invalid switch, '$argv[$arg_count]'"
      goto help
```

```
    breaksw
   default:
    set FILELIST = "$FILELIST $argv[$arg_count]"
    set HAVE_FILE = "TRUE"
    breaksw
 endsw
 @ arg_count++
end

if($HAVE_FILE == "FALSE") then
 echo "ERROR: must supply input filename"
 goto help
endif

echo "infiles = $FILELIST"
echo "outdir = $outdir"
set month = `date | nawk '{print substr($0,5,3)}'`
set day   = `date | nawk '{print substr($0,9,2)}'`
set year  = `date | nawk '{print substr($0,25,4)}'`
set time  = `date | nawk '{print substr($0,12,8)}'`
set logfile = ${0}_log_${month}_${day}_${year}_${time}
echo "" >! $logfile
echo  "------------------------------------------------------------"  >>  $logfile
echo "Begin logfile: $logfile" >> $logfile
echo "" >> $logfile
set command_string = $0
@ arg_count = 1
while ( $arg_count <= $#argv )
 set command_string = "$command_string $argv[$arg_count]"
 @ arg_count++
end
echo "Command line:" >> $logfile
echo "  $command_string" >> $logfile
echo ""
echo "" >> $logfile
echo $version
echo $version >> $logfile
echo  "------------------------------------------------------------"  >>  $logfile
echo "Invoked on `date` by `whoami` on host `hostname`" >> $logfile
echo "from directory:" >> $logfile
echo "" >> $logfile
echo "   `pwd`" >> $logfile
echo "" >> $logfile
echo "Process ID: $$" >> $logfile
echo "System:     $ENV_TYPE" >> $logfile
echo "Server:     `ypwhich`" >> $logfile
echo  "------------------------------------------------------------"  >>  $logfile
echo ""
echo " " >! $outdir/files_processed
echo "" >> $logfile
echo  "------------------------------------------------------------"
echo  "------------------------------------------------------------"  >>  $logfile

#
# Read selected image from PhotoCD disk.
#
foreach FILE ($FILELIST)
 echo "((working on input file $FILE and lovin' every minute of it...))"
   if ($FILE < 10) then
    set photoCDnum = $FILE
    set pcdnum = "00$FILE"
    set FILE = "photoCD000$FILE"
   else if ($FILE < 100) then
    set photoCDnum = $FILE
    set pcdnum = "0$FILE"
    set FILE = "photoCD00$FILE"
   else
    set photoCDnum = $FILE
    set pcdnum = "$FILE"
    set FILE = "photoCD0$FILE"
   endif
```

```
  foreach RES ($res_set)
    echo ""
     echo "~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~"
    echo "Reading PhotoCD YCC image number $photoCDnum"
     echo "~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~"
    echo ""
    echo "Reading PhotoCD YCC image number $photoCDnum..." >> $logfile
    setenv TIC_DEF_CD /cdrom/cdrom0/photo_cd/images/
    echo "((extracting $RES))"
     /inhouse/islsoftware/bin/tic $RES  \
                /cdrom/cdrom0/photo_cd/images/img0$pcdnum.pcd $outdir/${FILE}_$RES  \
                -t IMPS  -m ycc
    echo "/inhouse/islsoftware/bin/tic $RES  \
                /cdrom/cdrom0/photo_cd/images/img0$pcdnum.pcd $outdir/${FILE}_$RES  \
                -t IMPS  -m ycc" >> $logfile
#
# Check if PhotoCD image exists.
#
    imginfo $outdir/${FILE}_$RES >& /dev/null
    if ($status) then
      echo "ERROR creating YCC image $outdir/${FILE}_${RES}"
      echo "ERROR creating YCC image $outdir/${FILE}_${RES}" >> $logfile
      exit 1
    endif
    echo "((Before DSIZE...$RES))"

    foreach DSIZE ($size)
      if (($RES == "Base16") && ($DSIZE == "tmb")) then
        echo "((After DSIZE...thumb))"
        echo ""
#
# Sample down Photo CD images to appropriate sizes.
#
        echo ""
        echo "" >> $logfile
        echo "((Sampling down Base/16 Photo CD image to thumbnail size...))"
        echo "Sampling down Base/16 Photo CD image to thumbnail size..." >> $logfile
        echo "pplus -i $outdir/${FILE}_${RES}    \
                        -o $outdir/${FILE}_${RES}_${DSIZE}    \
                        -c "model $thumb_size_model"    \
                        -d u"
        echo ""
        echo "pplus -i $outdir/${FILE}_${RES}    \
              -o $outdir/${FILE}_${RES}_${DSIZE}    \
              -c "model $thumb_size_model"    \
              -d u " >> $logfile
        pplus -i $outdir/${FILE}_${RES}    \
              -o $outdir/${FILE}_${RES}_${DSIZE}    \
              -c "model $thumb_size_model"    \
              -d u >> $logfile
        if ($status != 0) then
          echo ""
          echo "" >> $logfile
          echo "    ERROR: pplus failed to run thumb_size_model"
          echo "    ERROR: pplus failed to run thumb_size_model"  >> $logfile
          exit 1
        endif
#
# Convert Photo YCC to monitor/hardcopy.
#
        echo ""
        echo "" >> $logfile
        echo "((Converting Photo YCC to monitor))"
        echo "Converting Photo YCC to monitor" >> $logfile
        echo "pplus -i $outdir/${FILE}_${RES}_${DSIZE}    \
                        -o $outdir/${FILE}_${RES}_${DSIZE}_shm2    \
                        -c "model $ycc_model"    \
                        -d u"
        echo ""
        echo "pplus -i $outdir/${FILE}_${RES}_${DSIZE}    \
              -o $outdir/${FILE}_${RES}_${DSIZE}_shm2    \
              -c "model $ycc_model"    \
```

```
        -d u" >> $logfile
    pplus -i $outdir/${FILE}_${RES}_${DSIZE}   \
          -o $outdir/${FILE}_${RES}_${DSIZE}_shm2   \
          -c "model $ycc_model"   \
          -d u >> $logfile
    if ($status != 0) then
      echo ""
      echo "" >> $logfile
      echo "    ERROR: pplus failed to run model $ycc_model"
      echo "    ERROR: pplus failed to run model $ycc_model"  >> $logfile
      exit 1
    endif
    echo " "

    echo " " >> $logfile
    if ($rotate == "TRUE") then
      c4v -i $outdir/${FILE}_${RES}_${DSIZE}_shm2   \
                  -o $outdir/${FILE}_${RES}_${DSIZE}_shm2_90   \
                  -r ccw -tmpdir /space/daily/dewing
      \rm $outdir/${FILE}_${RES}_${DSIZE}_shm2.*
      mvimps $outdir/${FILE}_${RES}_${DSIZE}_shm2_90  \
                  $outdir/${scene}_${DSIZE}
    else
      cpimps $outdir/${FILE}_${RES}_${DSIZE}_shm2  \
                  $outdir/${scene}_${DSIZE}
    endif
    echo ""
#
# Create final softcopy (band sequential) and hardcopy images (labeled).
#
    echo "(($outdir/${scene}_${DSIZE} will be concatenated to a band\
                  sequential file $outdir/${scene}_${DSIZE}.lum))"
    echo "$outdir/${scene}_${DSIZE} will be concatenated to a band\
                  sequential file $outdir/${scene}_${DSIZE}.lum" >> $logfile
    cat  $outdir/${scene}_${DSIZE}.red  $outdir/${scene}_${DSIZE}.grn\
                  $outdir/${scene}_${DSIZE}.blu > $outdir/${scene}_${DSIZE}.lum

    echo "((We have successfully created final output image \
                  $outdir/${scene}_${DSIZE}.lum))"
    echo ""
    echo "We have successfully created final output image \
                  $outdir/${scene}_${DSIZE}.lum" >> $logfile
    echo "$outdir/${scene}_${DSIZE}.lum" >> $outdir/files_processed
  endif


  if (($RES == "Base") && ($DSIZE == "sc")) then
    echo "((After DSIZE...image))"
    echo ""
    echo "" >> $logfile
    echo "((Sampling down Base Photo CD image to image size...))"
    echo "Sampling down Base Photo CD image to image size..." >> $logfile
    echo "pplus -i $outdir/${FILE}_${RES}   \
                  -o $outdir/${FILE}_${RES}_${DSIZE}   \
                  -c "model $image_size_model"   \
                  -d u "
    echo ""
    echo "pplus -i $outdir/${FILE}_${RES}   \
          -o $outdir/${FILE}_${RES}_${DSIZE}   \
          -c "model $image_size_model"   \
          -d u " >> $logfile
    pplus -i $outdir/${FILE}_${RES}   \
          -o $outdir/${FILE}_${RES}_${DSIZE}   \
          -c "model $image_size_model"   \
          -d u >> $logfile
    if ($status != 0) then
      echo ""
      echo "" >> $logfile
      echo "    ERROR: pplus failed to run image_size_model"
      echo "    ERROR: pplus failed to run image_size_model"  >> $logfile
      exit 1
    endif
```

```
#
# Convert Photo YCC to monitor/hardcopy.
#
      echo ""
      echo "" >> $logfile
      echo "((Converting Photo YCC to monitor))"
      echo "Converting Photo YCC to monitor" >> $logfile
      echo "pplus -i $outdir/${FILE}_${RES}_${DSIZE}   \
                        -o $outdir/${FILE}_${RES}_${DSIZE}_shm2   \
                        -c "model $ycc_model"   \
                        -d u "
      echo ""
      echo "pplus -i $outdir/${FILE}_${RES}_${DSIZE}   \
            -o $outdir/${FILE}_${RES}_${DSIZE}_shm2   \
            -c "model $ycc_model"   \
            -d u " >> $logfile
      pplus -i $outdir/${FILE}_${RES}_${DSIZE}   \
            -o $outdir/${FILE}_${RES}_${DSIZE}_shm2   \
            -c "model $ycc_model"   \
            -d u >> $logfile
      if ($status != 0) then
        echo ""
        echo "" >> $logfile
        echo "    ERROR: pplus failed to run model $ycc_model"
        echo "    ERROR: pplus failed to run model $ycc_model"  >> $logfile
        exit 1
      endif
      echo " "
      echo " " >> $logfile
      if ($rotate == "TRUE") then
        c4v -i $outdir/${FILE}_${RES}_${DSIZE}_shm2   \
            -o $outdir/${FILE}_${RES}_${DSIZE}_shm2_90   \
            -r ccw -tmpdir /space/daily/dewing
        \rm $outdir/${FILE}_${RES}_${DSIZE}_shm2.*
        mvimps $outdir/${FILE}_${RES}_${DSIZE}_shm2_90  \
            $outdir/${scene}_${DSIZE}
      else
        cpimps $outdir/${FILE}_${RES}_${DSIZE}_shm2  \
            $outdir/${scene}_${DSIZE}
      endif
      echo ""
#
# Create final softcopy (band sequential) and hardcopy images (labeled).
#
      echo "(($outdir/${scene}_${DSIZE} will be concatenated to a band\
            sequential file $outdir/${scene}_${DSIZE}.lum))"
      echo "$outdir/${scene}_${DSIZE} will be concatenated to a band\
            sequential file $outdir/${scene}_${DSIZE}.lum" >> $logfile
      cat  $outdir/${scene}_${DSIZE}.red  $outdir/${scene}_${DSIZE}.grn\
            $outdir/${scene}_${DSIZE}.blu > $outdir/${scene}_${DSIZE}.lum


      echo "((We have successfully created final output image \
            $outdir/${scene}_${DSIZE}.lum))"
      echo ""
      echo "We have successfully created final output image \
            $outdir/${scene}_${DSIZE}.lum" >> $logfile
      echo "$outdir/${scene}_${DSIZE}.lum" >> $outdir/files_processed
     endif


     if (($RES == "16Base") && ($DSIZE == "hc")) then
       echo "((After DSIZE...print))"
       echo ""
       echo "" >> $logfile
       echo "((Sampling down 16Base Photo CD image to print size...))"
       echo "Sampling down 16Base Photo CD image to print size..." >> $logfile
       echo "pplus -i $outdir/${FILE}_${RES}   \
                        -o $outdir/${FILE}_${RES}_${DSIZE}   \
                        -c "model $print_size_model"   \
                        -d u "
       echo ""
```

```
      echo "pplus -i $outdir/${FILE}_${RES}   \
            -o $outdir/${FILE}_${RES}_${DSIZE}   \
           -c "model $print_size_model"   \
           -d u " >> $logfile
      pplus -i $outdir/${FILE}_${RES}   \
            -o $outdir/${FILE}_${RES}_${DSIZE}   \
           -c "model $print_size_model"   \
           -d u >> $logfile
      if ($status != 0) then
       echo ""
       echo "" >> $logfile
       echo "    ERROR: pplus failed to run print_size_model"
       echo "    ERROR: pplus failed to run print_size_model"  >> $logfile
       exit 1
      endif
#
# Convert Photo YCC to monitor/hardcopy.
#
      echo ""
      echo "" >> $logfile
      echo "((Converting Photo YCC to monitor))"
      echo "Converting Photo YCC to monitor" >> $logfile
      echo "pplus -i $outdir/${FILE}_${RES}_${DSIZE}   \
                        -o $outdir/${FILE}_${RES}_${DSIZE}_shm2   \
                        -c "model $ycc_model"   \
                        -d u"
      echo ""
      echo "pplus -i $outdir/${FILE}_${RES}_${DSIZE}   \
            -o $outdir/${FILE}_${RES}_${DSIZE}_shm2   \
           -c "model $ycc_model"   \
           -d u" >> $logfile
      pplus -i $outdir/${FILE}_${RES}_${DSIZE}   \
            -o $outdir/${FILE}_${RES}_${DSIZE}_shm2   \
           -c "model $ycc_model"   \
           -d u >> $logfile
      if ($status != 0) then
       echo ""
       echo "" >> $logfile
       echo "    ERROR: pplus failed to run model $ycc_model"
       echo "    ERROR: pplus failed to run model $ycc_model"  >> $logfile
       exit 1
      endif
      echo " "
      echo " " >> $logfile
      if ($rotate == "TRUE") then
        c4v -i $outdir/${FILE}_${RES}_${DSIZE}_shm2   \
                        -o $outdir/${FILE}_${RES}_${DSIZE}_shm2_90   \
                        -r ccw -tmpdir  /space/daily/dewing
        \rm $outdir/${FILE}_${RES}_${DSIZE}_shm2.*
        mvimps $outdir/${FILE}_${RES}_${DSIZE}_shm2_90 \
                        $outdir/${scene}_${DSIZE}
      else
        cpimps $outdir/${FILE}_${RES}_${DSIZE}_shm2 \
                        $outdir/${scene}_${DSIZE}
      endif
      echo ""


      echo "((We have successfully created final output image \
                        $outdir/${scene}_${DSIZE}))"
      echo ""
      echo "We have successfully created final output image \
                        $outdir/${scene}_${DSIZE}" >> $logfile
      echo "$outdir/${scene}_${DSIZE}" >> $outdir/files_processed
     endif

    end #foreach dsize
  end  #foreach res
#
# delete intermediate images
#
  \rm $outdir/${FILE}*.red $outdir/${FILE}*.grn $outdir/${FILE}*.blu $outdir/${FILE}*.doc
```

```
  \rm $outdir/*_sc.red $outdir/*_sc.grn $outdir/*_sc.blu $outdir/*_sc.doc
  \rm $outdir/*_tmb.red $outdir/*_tmb.grn $outdir/*_tmb.blu $outdir/*_tmb.doc

end  #foreach file

#
# Write completion status to log file.
#

echo "" >> $logfile
echo  "------------------------------------------------------------"  >>  $logfile
echo "Completed on `date` by `whoami` on host `hostname`" >> $logfile

#
# Write completion status to screen.
#

echo ""
echo  "------------------------------------------------------------"
echo "Completed on `date` by `whoami` on host `hostname`"

exit 0

#
# Pseudo Subroutines
#

help:
echo ""
echo "  Zoom  /  Crop  script (Version $version)"
echo ""
echo " Usage:"
echo ""
echo " color_adjust_wende <in_image1> [<in_image2>...<in_imageN>] "
echo " [-o <outdir>] [-i <scene name>] [-vr] "
echo " where:"
echo "    <in_imageX> Image photoCD image number.   This script assumes"
echo "                that any <in_imageX> 0 through 150 is a photoCD image number"
echo "                This script assumes the photoCD is mounted on the current"
echo "                system under /cdrom/cdrom0."
echo "    -o <outdir> Output directory where all temporary files and final images"
echo "                will be stored"
echo "    -i <scene>  image identifier to be used in file name
echo "    -v          Initial image as read from PhotoCD has"
echo "                a width that is smaller than the height"
echo "    -r          rotate final image 90 degrees ccw"
echo " "
echo "    For help, use the -? flag, or use no arguments"

exit 1
```

EDS_SHM2.MOD

```
* Convert YCC to Luma, Chroma1, Chroma2
shift 0 -156 -137
scale 0.005498039 0.008976661 0.007372457
* Convert to CCIR 709 RGB Gamma Space Code Values
matrix /home/dewing/MODELS/lcc_2_rgb709.mat
scale 1000
clip 0 1402
* Compress the highlights to prevent clipping
shape /home/dewing/MODELS/rgb709_remap2.tab
scale 255
```

IMAGE_DOWN.MOD

```
* This model samples down a base (512x768) image to roughly 4x6 size, assuming 72dpi, using the 5774 filter
*  filter 1107 is down by 2
*  filter 5774 is down by 1.75
*  filter 1272 is down by 1.5
*
* Crop to size divisible by 4
crop /lines_centered=504 /pixels_centered=756
* Prefilter
convolve 5774 /normalize /pixpad
* Resize to 432 pixels x 288 lines
resample /pixels=432 /lines=288
```

NEWTHUMB_DOWN.MOD

```
* This model samples down a base/16 (128x192) image to roughly 2x1 size, assuming 72dpi, using the 1272 filter
*  filter 1107 is down by 2
*  filter 5774 is down by 1.75
*  filter 5680 is down by 1.5
*  filter 1272 is down by 1.25
*
* Crop to size divisible by 4
crop /lines_centered=125 /pixels_centered=190
* Prefilter
convolve 5774 /normalize /pixpad
* Resize to 108 pixels x 72 lines
resample /pixels=108 /lines=72
```

PRINT_DOWN.MOD

```
* This model samples down a 16base (2048x3072) image to roughly 4x6 size, assuming 502dpi, using no filter
*  filter 1107 is down by 2
*  filter 5774 is down by 1.75
*  filter 1272 is down by 1.5
*
* Crop to size divisible by 4
crop /lines_centered=2048 /pixels_centered=3012
```

The following PPLUS script was used to transform images to printer format, in preparation of the hardcopy phase for the primary study. Models used within this script are presented below.

MAKE_PRINTS

```
# Script to generate prints for image processing output path
# for Wende Dewing
#
# Doug Christoffel / Wende Dewing
#
# Version 1.0 1/6/98
#
# Usage:
#   make_prints -df data_file -if image_file -id input_directory -od output_directory
#

#
# Initialize variables
#
set version = "Version 1.0 1/6/98"
@ arg_count = 1
while( $arg_count <= $#argv )
  switch($argv[$arg_count])
    case -[hH]:
     goto gen_help
     breaksw
    case -[dD][fF]
     @ arg_count++
     set datafile = $argv[$arg_count]
     breaksw
    case -[iI][fF]
     @ arg_count++
     set imgfile = $argv[$arg_count]
     breaksw
    case -[iI][dD]
     @ arg_count++
     set indir = $argv[$arg_count]
     breaksw
    case -[oO][dD]
     @ arg_count++
     set outdir = $argv[$arg_count]
     breaksw
    default:
     echo ""
     echo "   ERROR: Listen you hosehead, you need to give a data file name."
     echo ""
     goto gen_help
  endsw
  @ arg_count++
end

if( $arg_count != 9 ) then
  echo ""
  echo "   ERROR: Illegal number of command line arguments"
  echo ""
  goto gen_help
endif

#
# Set environment variable to force c4v to output IMPS images.
#
setenv SIL_DEF_FILE_FORMAT sil_imps

#
# Read in image names and corresponding orientations from the image file.
#
set image_file_names = `nawk '{if(NR>1) print $1}' $imgfile`
set image_file_orients = `nawk '{if(NR>1) print $2}' $imgfile`

#
# Read in image processing data informatation from the data file.
```

```
#
set image_data = `nawk '{print $0}' $datafile`

#
# Loop over each line of data.
#
set num_data_entries = `wc -l $datafile | nawk '{print $1}'`
@ i = 0
while($i < $num_data_entries)

 #
 # Assume 15 data values per line in the data file.
 #
 @ index = (15 * $i) + 1
 setenv subject $image_data[$index]
 @ index++
 setenv gui $image_data[$index]
 @ index++
 setenv space $image_data[$index]
 @ index++
 setenv image_id $image_data[$index]
 @ index++
 setenv gamma $image_data[$index]
 @ index++
 setenv purity $image_data[$index]
 @ index++
 setenv temp $image_data[$index]
 @ index++
 setenv quality_rating_1 $image_data[$index]
 @ index++
 setenv r_offset $image_data[$index]
 @ index++
 setenv g_offset $image_data[$index]
 @ index++
 setenv b_offset $image_data[$index]
 @ index++
 setenv contrast_offset $image_data[$index]
 @ index++
 setenv bright_offset $image_data[$index]
 @ index++
 setenv edit_time $image_data[$index]
 @ index++
 setenv quality_rating_2 $image_data[$index]

 #
 # Find input image using the image identifier from data file and the
 # corresponding image name in the image file.
 #
 set input_image = $indir/{$image_file_names[$image_id]:r}_hc

 #
 # Create output image name.
 #
 set output_image_root = {$subject}{$gui}_{$image_id}_{$gamma}{$purity}{$temp}
 set output_image = $outdir/$output_image_root

 #
 # Process each input image using the offset data read in from the data file.
 #
 pplus -i $input_image \
      -o /tmp/temp_1  \
      -c "model /home/dewing/MODELS/apply_edits.mod"    \
      -lslocal  \
      -f imps

 pplus -i /tmp/temp_1  \
      -o /tmp/temp_2  \
      -c "model /home/dewing/MODELS/nl709rgb_2_edge7.mod"    \
      -lslocal  \
      -f imps

 \mv /tmp/temp_2.doc /tmp/temp_1.doc
```

```
 \mv /tmp/temp_2.red /tmp/temp_1.red
 \mv /tmp/temp_2.grn /tmp/temp_1.grn
 \mv /tmp/temp_2.blu /tmp/temp_1.blu

 #
 # Label the processed image.  Place labels at the top for vertical images.
 # Place labels on the right side for horizontal images. For horizontal images,
 # rotate the images 90 degrees counter-clockwise, apply the label at the top
 # and then rotate back to the original orientation.
 #
 if( ($image_file_orients[$image_id] == "h") || \
     ($image_file_orients[$image_id] == "H") ) then
  echo "RELAX Cookie Maker...rotating horizontal image before applying label..."
   c4v -r ccw -tmpdir /tmp -i /tmp/temp_1 -o /tmp/temp_2
   \mv /tmp/temp_2.doc /tmp/temp_1.doc
   \mv /tmp/temp_2.red /tmp/temp_1.red
   \mv /tmp/temp_2.grn /tmp/temp_1.grn
   \mv /tmp/temp_2.blu /tmp/temp_1.blu
 endif

 #
 # Pad the image to 16base dimensions (2048 pixels x 3072 lines) with a
 # white border along the top and right side of the image.
 #
 pplus -i /tmp/temp_1  \
       -o /tmp/temp_2  \
       -c "PAD 255 /LINES_OUT=3072 /PIXELS_OUT=2048 /LSTART=61 /PSTART=1" \
       -lslocal  \
       -f imps

 #
 # Add image name label to the image.
 #
 pplus -i /tmp/temp_2  \
       -o /tmp/$output_image_root  \
       -c "LABEL /LSTART=1 /PSTART=50"  \
       -lslocal  \
       -f imps

 #
 # At this point, all images will be vertical regardless of whether or not the
 # original input image was vertical or horizontal. Rotate images 90 degrees
 # clockwise for printing.
 #
 c4v -r cw -tmpdir /tmp -i /tmp/$output_image_root -o $output_image

 #
 # Remove temp images.
 #
 \rm /tmp/temp_1.*
 \rm /tmp/temp_2.*
 \rm /tmp/$output_image_root.*
 @ i++
end #while loop
exit 0

#
# Pseudo Subroutines
#
gen_help:
echo ""
echo "Run script"
echo "(Version $version)"
echo ""
echo "Usage:  $0"
echo "                  -df data_file (required)"
echo "                  -if image_file (required)"
echo "                  -id input_directory (required)"
echo "                  -od output_directory (required)"
echo "                  [-h] (optional help info)"
echo ""
exit 1
```

APPLY_EDITS.MOD

```
*  This model takes data from a ColorTool output file and applies it
*  to an imps format image in nonlinear gamma corrected RGB space

variable r_offset 0  / translate
variable g_offset 0  / translate
variable b_offset 0  / translate
variable bright_offset 0  / translate
variable contrast_offset 0  / translate

* apply RGB edits
save  / buffer=1
scale r_offset g_offset b_offset
scale 0.005 0.005 0.005
add  / buffer=1
save  / buffer=3

* apply brightness edits
recall  / buffer=1
scale bright_offset bright_offset bright_offset
scale 0.005 0.005 0.005
add  / buffer=3

* apply contrast edits
shift -125 -125 -125
save  / buffer=5
scale contrast_offset contrast_offset contrast_offset
scale 0.005 0.005 0.005
add  / buffer=5
shift 125 125 125

* clip code values to within 0-255
clip 0 255
```

NL709RGB_@_EDGE7.MOD

```
* input= Wende's preprocessed images, in nonlin 709 rgb

scale 7.33 7.33 7.33
shift  810 810 810
shape  / home / pellow / matlut / unfgamma_ccir_postpk_ver000.lut;
shift  -355 -355 -355
scale 0.1 0.1 0.1

* convert CCIR709-RGB TO D65-XYZ
matrix  / home / pellow / matlut / ccir709_d65_pmat.mat;
matrix  / home / pellow / matlut / custom_d65_to_d50_vonkries.mat;

* convert D50-XYZ to GB-RGB
matrix  / home / pellow / matlut / xyzd50_to_gb-rgb.mat;
log10
scale 1000 1000 1000
shift  73 73 73
shape  / home / pellow / matlut / test1.lut;
scale -.001 -.001 -.001
exp10
matrix  / home / pellow / matlut / crt-edge7-041598-lin.mat
log10
matrix  / home / pellow / matlut / crt-edge7-041598-log3x3.mat
scale -1000 -1000 -1000
shift 20 -20 -80
shape  / home / pellow / matlut / edge7-visneutral.lut
scale .1 .1 .1
```

APPENDIX C

Color Tool Description

This appendix discusses the image processing that is conducted by a program referred to as the color tool. This program was written to allow participants to easily interact with color images with the goal of enhancing the color of the image. Many commercially available software packages exist that might fulfill this goal. However, this tool also allows the experimenter to record information about the participants' behavior and to manipulate the color of the image in a known way.

When used, color tool reads a pair of script files to determine the names of the input files and the order these files are to be presented. Once this is complete, two files, a video resolution image and a thumbnail, are read into memory. These input files are expected to be 8 bits per color channel and the color channels are expected to be sequential (i.e., non-interleved). The image data is then processed as follows.

1) The data is reformatted to a native Macintosh format where each image is represented as an array of structures with each structure representing a 16 bit per color, signed RGB triplet. Although the data is reformatted at this stage the data are not altered. Therefore, the values in this 16 bit per color RGB triplet remain between 0 and 255. This data is held in memory for processing and displaying at later times. In fact, each image update begins with the data from this processing stage.
2) When the user selects a new color balance point, a set of offset values are updated by determining the new offset value selected by the user. These offset values represent changes in the red, green, blue, brightness, and contrast of the images. Notice that the image data is not altered in response to the selection of a new balance point, only these offset values are updated.
3) When red, green, or blue is added or subtracted from the image, the image data is processed to allow the appropriate color plane pixel values to be multiplied by a constant. This operation is represented in the following three equations:

   NewRedPixel = RedPixel + RedOffset*RedPixel
   NewBluePixel = BluePixel + BlueOffset*BluePixel
   NewGreenPixel = GreenPixel + GreenOffset*BluePixel

   Note that only one of these operations alter the data if only one offset value is not equal to zero.
4) When brightness is added or subtracted from the image, all three color planes are processed by multiplying the pixel values by the appropriate constant. This operation is represented in the following three equations:

   NewRedPixel = RedPixel + BrightnessOffset*RedPixel
   NewBluePixel = BluePixel + BrightnessOffset*BluePixel
   NewGreenPixel = GreenPixel + BrightnessOffset*BluePixel

   Note that all three of these operations alter the data each time a new brightness position is selected.
5) When contrast is added or subtracted from the image, a three stage process is completed where the contrast pivot point is subtracted from the data, the data in each color plane is multiplied by an offset value, and the contrast pivot point is added to the data. This operation can be represented by the follow nine lines of pseudocode.

   RedPixel = RedPixel - Pivot
   BluePixel = BluePixel - Pivot
   GreenPixel = GreenPixel - Pivot
   RedPixel = RedPixel + ContrastOffset*RedPixel

BluePixel = BluePixel + ContrastOffset*BluePixel
GreenPixel = GreenPixel + ContrastOffset*GreenPixel
RedPixel = RedPixel + Pivot
BluePixel = BluePixel + Pivot
GreenPixel = GreenPixel + Pivot

Note that all operations alter the data each time a new contrast position is selected.

6) Once all calculations are completed, each RGB value is clipped to the 0 to 255 range of values. It should be noted that this tool applied the edit values to the original image data after all edits had been made rather than applying edit values to the edited image. Therefore, a user could truly undo an edit without loss of data due to clipping. Most commercially available graphic editing programs manipulate original image data with each edit, resulting in cascaded clipping operations.
7) The data is reformatted into PICT file format for display to the monitor. It should be noted, that the data for the full sized video image and the thumbnails is processed in the same way. However, the thumbnails in the ring around are always processed with offset values that differ by a fixed amount from the offsets for the full resolution video image. This allows the thumbnails in the ring around to be displayed with different red, green, blue, brightness, and contrast balance.
8) Once the user completes all color edits on an image, the offset values are written to a data file and the next image is read into memory for processing and display.

Figure C1: Color Tool Rating Screen for Pilot Study

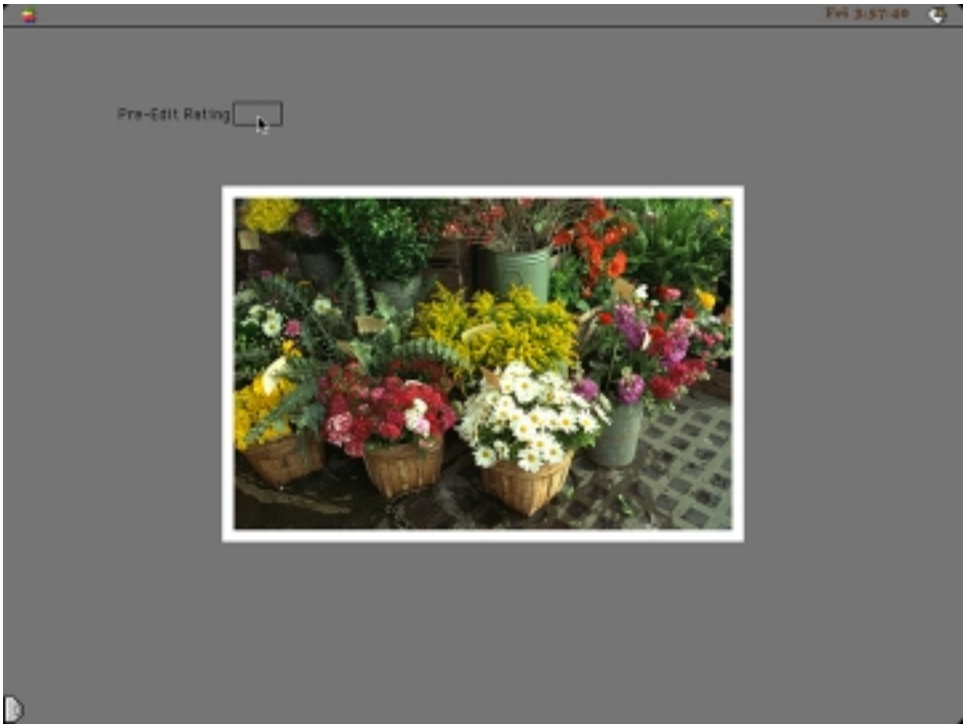


Figure C2: Color Tool Slider Screen for Pilot Study

Figure C3: Color Tool Ring-Around Screen for Pilot Study

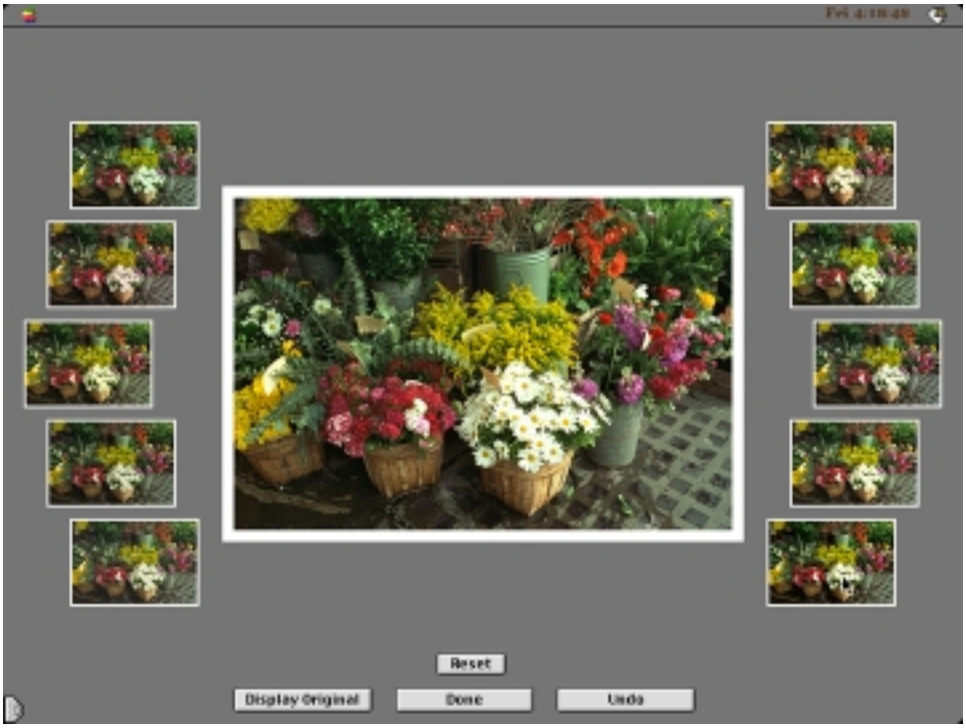


Figure C4: Color Tool Rating Screen for Primary Study

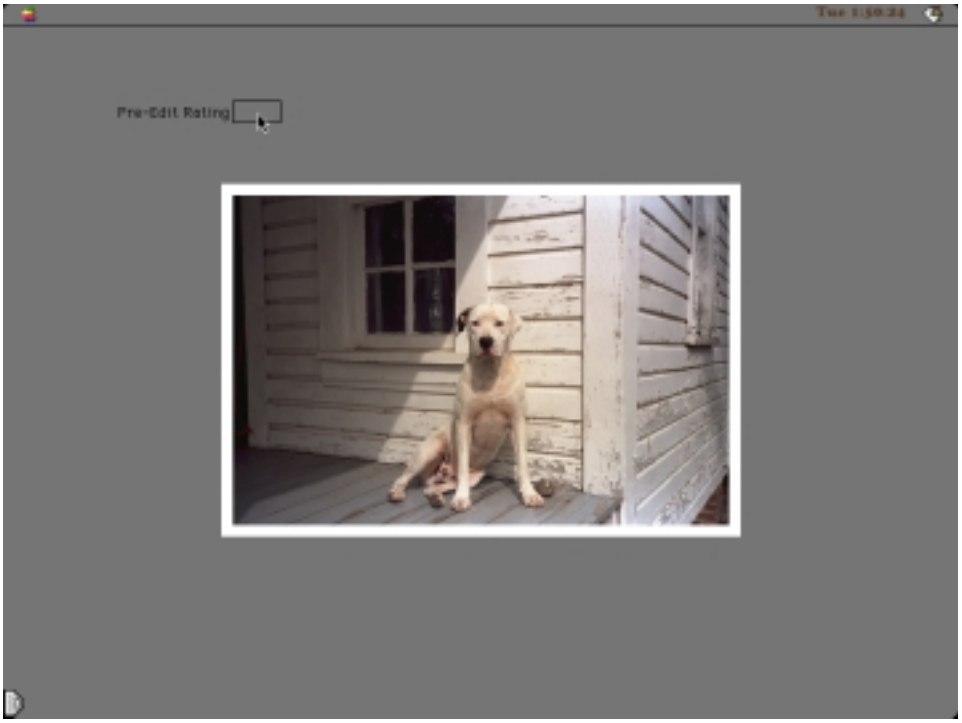
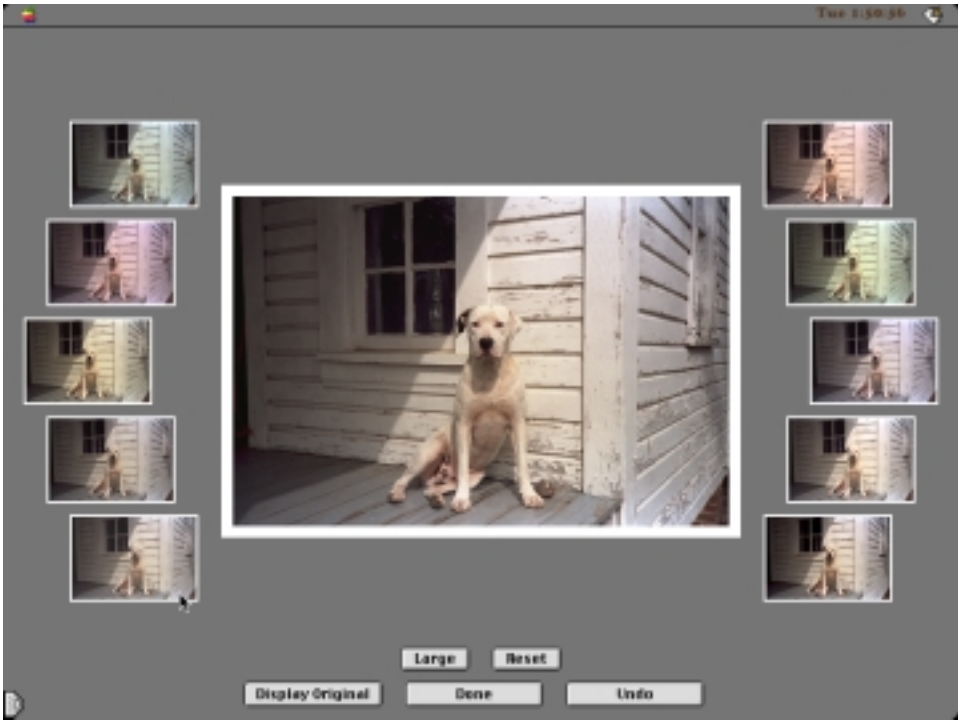


Figure C5: Color Tool Editing Screen for Primary Study



APPENDIX D

Participant Instructions

Figure D1: Pilot Study Instructions

Introduction

Thank you for helping us out today! In this session you will be looking at computer simulations of photographic prints, judging them for their overall color quality and editing them to your liking. All photographs will be presented one at a time on a computer monitor. There will be a total of 36 photographs of 6 unique scenes. For each of the photographs you will:

1. provide an overall color quality rating (referred to as the pre-edit rating),
2. edit the photograph to your liking, and
3. provide a second overall color quality rating (referred to as the post-edit rating).

Pre-Edit Rating Procedure

I would like you to evaluate the color quality of each photograph using a simple rating procedure. This procedure will allow you to estimate how good or poor the overall color quality of a photograph is, in terms of all color photographs you have ever seen. There may be many factors that influence your judgment of color quality. However, please try to ignore such factors as marks on the photographs and whether or not you like the subject of the photograph. I am interested in your assessment of how good or poor each photo is in terms of what, YOU personally, consider color quality in photographs. There are, then, no correct or incorrect answers. At this point, I would like you to write down how you define color quality. I am not looking for a dictionary definition. Include in your statement a description of all factors you feel influence the color quality of photographs.

Next, I would like you to think of a photograph you've seen in the past that was of high color quality, as you defined it just now. This imagined reference should be based on your experience viewing photographs and should meet all of the requirements outlined in your definition of color quality. Write down a brief description of the photograph including; subject, location, composition, and what you liked about the colors in the photo. Does this photo meet all of the requirements of color quality that you defined above? If not, please write down where it falls short. This photo will be referred to as the modulus and will be assigned a value of 200. The score assigned to the modulus should remain constant throughout the study.

To assess color quality, I will ask you to assign a number to each photograph. This number should represent a ratio between the modulus and the photo you are viewing on the computer. Judging the color quality ratios of each photograph you see is a simple procedure. First, determine whether the photograph is better or worse than the modulus. Next, determine how much the photo differs from your modulus. For example, is the photo 30% or 50% different than the modulus. Then assign the photograph a number proportional to the difference value. For example, if you believe the photo is 30% better than your imagined reference it would receive a score 30% higher than the reference score. Since the modulus is assigned a value of 200, the photo would receive a score of 260. Likewise, if the photograph being viewed is 50% worse than your modulus, you would assign the photograph a number 50% lower than your modulus (or a score of 100). You may use the reference card provided as a guide for determing ratings. However, you are not limited only to the ratings depicted on the card. You may use any whole number from 0 on up for your rating. Zero should represent a condition of "no color quality" such as, when there is no color at all on the photograph (like a solid white, gray, or black field). I do not want you to rate photographs on a limited scale of 0-to-200. Instead, assign the photographs a rating based on their color appearance compared to the color appearance of your imagined reference.

If you approach the task in a casual manner it will probably be easier for you. Simply ask yourself two questions at each rating prompt. (1) Is the photo better or worse than the modulus? (2) How much better/worse? Use your answers to select a color quality rating. There is no need to try to remember the numbers that you have assigned to previous photographs. Your ratings should be based solely on the modulus. Do you have any questions? Before we continue, I will show you a sample set of photographs so that you may practice the rating technique.

For the real trials, each photograph will be displayed on the computer along with a prompt inviting you to enter your pre-edit rating. Type in the number you would like to assign the photo and hit the return/enter key.

Color Editing Procedure

I would like you to edit the photographs for color balance using a special ColorTool. Each photo will be displayed on the computer along with a set of controls that will enable you to adjust color, brightness, and contrast. You will be using two versions of the ColorTool; one featuring sliders and another featuring a ring-around. As I describe the features of each ColorTool, I will demonstrate how to use the controls.

On the slider version of the ColorTool, a photograph is presented along with a set of 5 controls. From top to bottom, the control dimensions are red, green, blue, brightness, and contrast. To activate a slider click either on the pointer or the scale using the mouse. All sliders are initialized to 0 which lies at the center of the scale. To increase color, brightness, and contrast click to the right of 0. To decrease any dimension click to the left of 0. Notice that decreases in red, green, and blue bring about an increases in cyan, magenta, and yellow, respectively. At the bottom of the screen you will see 4 buttons; *Reset*, *Done*, *Display Original*, and *Undo*. *Reset* will return all sliders to their 0 position, meaning all of your edits will be erased. *Undo* will erase only the last edit you made, leaving all other edits intact. *Display Original* will show you the photo as it appeared before you made any edits. Click and hold this button to view the original photo, release the button to see the current photo. *Done* will save any edits you have made and move to the next screen. Only click this button when you have completely finished editing the

photo. Once you select *Done* you cannot go back. Do you have any questions? Now I would like you to take a few minutes to practice with the sliders. When you feel comfortable with the controls you may stop.

On the ring-around version of the ColorTool, a photograph is presented along with a set of 10 thumbnails. The same color dimensions are presented in this version as in the last--from top to bottom; red, green, blue, brightness, and contrast. Thumbnails provide a preview of how the photograph will appear after an edit is applied. Thumbnails on the right preview increases in primary colors, brightness, and contrast, those on the left preview decreases in each dimension. If you feel the photograph needs improved color balance, look through the thumbnails to determine the direction of change desired. Using the mouse, click on the selected thumbnail and the photograph will update to show the change. You will also notice the thumbnails update to preview future edits in relation to the new current photograph. The buttons presented on the bottom of the screen are the same as those introduced in the slider version, and behave in the same manner. Do you have any questions? I would like you to take a few minutes to practice with the ring-around. When you feel comfortable with the controls you may stop.

Post-Edit Rating Procedure

Once you have clicked on the *Done* button you will be prompted to enter a second overall color quality rating. Use the same rating technique as that used for the pre-edit rating you provided earlier. That is, assign the edited photograph a rating based on its color appearance compared to the color appearance of your imagined reference. There is no need to try to remember the rating you assigned to the photograph prior to editing. Your color quality rating should be based solely on your imagined reference photo. Do you have any questions?

Now I will give you 4 practice trials so you may become comfortable with the procedures from start to finish. If you have questions as you go through the practice session feel free to ask them. Remember to ask yourself two questions at each rating prompt: (1) is the photo better or worse than the modulus? and (2) how much better / worse? Use your answers to select a rating.

That is the end of the practice session. Do you have any questions before we begin the real trials? Please turn away from the monitor while I set the computer up for the first set of trials....OK you can have a seat. Before you enter your pre-edit rating for this photograph, please look at the photo for 1 minute to allow your eyes to adjust to the monitor. I will let you know when the minute has passed....OK you may proceed.

Figure D2: Primary Study Instructions - Session Two

Introduction

Welcome. This is your second of four visits. In this session, you will be looking at computer simulations of photographic prints. For each photograph, you will be asked to provide a rating for overall color quality, edit the photo to your liking, and provide a second color quality rating. All photographs will be presented one at a time on the computer monitor. There will be a total of 54 photographs of 6 unique scenes.

Pre-Edit Rating Procedure

I would like you to evaluate the color quality of each photograph using a simple rating procedure. This procedure will allow you to estimate how good or poor the overall color quality of a photograph is, in terms of all color photographs you have ever seen. There may be many factors that influence your judgment of color quality. However, please try to ignore such factors as spots on the photographs, graininess, and whether or not you like the subject of the photograph. I am interested in your assessment of how good or poor each photo is in terms of what, YOU personally, consider color quality in photographs. There are, then, no correct or incorrect answers. At this point, I would like you to write down how you define color quality. I am not looking for a dictionary definition. Instead, include in your statement a description of all factors you feel influence the color quality of photographs.

Next, I would like you to think of a photograph you've seen in the past that was of high color quality, as you defined it just now. This imagined reference should be based on your experience viewing photographs and should meet all of the requirements outlined in your definition of color quality. Write down a brief description of the photograph including; subject, location, composition, and what you liked about the colors in the photo. Does this photo meet all of the requirements of color quality that you defined above? If not, please write down where it falls short. This photo will be referred to as your imagined reference and will be assigned a value of 200. The score assigned to this photograph should remain constant throughout the study.

To assess color quality, I will ask you to assign a number to each photograph. This number should represent a ratio between your imagined reference and the photo you are viewing on the computer. Judging the color quality ratios of each photograph you see is a simple procedure. First, determine whether the photograph differs in color quality from your imagined reference. Next, if the photograph is not equal in color quality to your reference, determine how much the photo differs from your reference. For example, is the photo 30% better or 50% worse than your reference. Then assign the photograph a number proportional to the difference value. For example, if you believe the photo is 30% better than your imagined reference, it would receive a score 30% higher than the reference score. Since your imagined reference is assigned a value of 200, the photo would receive a score of 260. Likewise, if the photograph being viewed is 50% worse than your imagined reference, you would assign the photograph a number 50% lower than your reference, or a score of 100. You may use the card provided here as a guide for determining ratings. however, you are not limited only to the ratings depicted on the card. Though the card represents ratings in 5% increments, you are free to use any whole number from 0 on up for your rating. Keep in mind that zero should represent a condition of "no color quality" such as, when there is no color at all on the photograph (like a solid

white, gray, or black field). I do not want you to rate photographs on a limited scale of 0 to 200. Instead assign the photographs a rating based on their color appearance compared to the color appearance of your imagined reference.

If you approach the task in a casual manner it will probably be easier for you. Simply ask yourself two questions at each rating prompt. (1) Does the photo differ from your imagined reference? And (2) if so, by how much? Use your answers to select a color quality rating. There is no need to try to remember the numbers that you have assigned to previous photographs. Your ratings should be based solely on your imagined reference. Do you have any questions? Before we continue, I will show you a sample set of photographs so that you may practice the rating technique.

For the real trials, each photograph will be displayed on the computer along with a prompt inviting you to enter your pre-edit rating. Type in the number you would like to assign the photo and hit the return or enter key.

Color Editing Procedure

I would like you to edit the photographs for color balance using a special ColorTool. The goal for this portion of the study is for you to obtain the best possible color balance for each photograph, based on your own personal preferences. As I describe the features of the ColorTool, I will demonstrate how to use the controls.

A photograph is presented along with a set of 10 thumbnails. Thumbnails provide a preview of how the photograph will appear after an edit is applied. Thumbnails on the right preview increases in primary colors, brightness, and contrast, those on the left preview decreases in each dimension. From top to bottom the control dimensions are red, green, blue, brightness, and contrast. If you feel the photograph needs improved color balance, look through the thumbnails to determine the direction of change desired. Using the mouse, click on the selected thumbnail and the photograph will update to show the change. You will also notice the thumbnails update to preview future edits in relation to the new current photograph.

At the bottom of the screen you will see 5 buttons; *Large/Small*, *Reset*, *Done*, *Display Original*, and *Undo*. The *Large/Small* button determines the degree of color change that results from one mouse-click on a thumbnail. To make gross color adjustments tot he photograph, the size button should read large. To make fine color adjustments, click on the size button until it reads small. *Reset* will return the photograph to its original appearance, meaning all of your edits will be erased. *Undo* will erase only the last edit you made, leaving all other edits intact. *Display Original* will show you the photo as it appeared before you made any edits. Click and hold this button to view the original photo, release the button to see the current photo. *Done* will save any edits you have made and move to the next screen. Only click this button when you have completely finished editing the photo. Once you select *Done* you cannot go back. Do you have any questions?

Please turn away from the monitor while I set the computer up for the first set of trials. OK we are ready to continue. Before you enter your pre-edit rating for this photograph, please look at the photo for 1 minute to allow your eyes to adjust to the monitor. I will let you know when the minute has passed. ... You will have finished the first set of six photographs when you reach a gray screen. Stop at this point and open the door. I will then set the computer up for the next set of trials. If you have questions or problems please page me, instructions are on the phone. OK you may proceed.

Figure D3: Primary Study Instructions - Session Three

Welcome Back. This is your third of four visits. In this session, you will again view computer simulations of photographic prints, rate them for overall color quality, and edit them for color balance. Today you will see 48 photographs of 6 unique scenes.

On your last visit, you provided a definition of color quality and a description of a high color quality photograph. For review, you defined color quality as [READ PARTICIPANT'S CQ DEFINITION]. And your imagined reference photo was described as [READ PARTICIPANT'S DESCRIPTION OF IMAGINED REFERENCE]. You'll recall, that your color quality ratings for each photograph should be based on these two items. Assign each photograph a rating based on its color appearance compared to the color appearance of your imagined reference. Ask yourself two questions at each rating prompt. (1) Does the photo differ from your imagined reference? And (2) if so, by how much? Use your answers to select a color quality rating. Use any whole number from zero on up. Keep in mind that zero should represent a condition where there is no color at all on the photograph, like a solid gray field. Remember to assign your ratings based only on your imagined reference rather than any photos you have previously viewed.

For the color balancing tasks you will use the same ColorTool presented in your last visit. Remember the goal for this portion of the study is for you to obtain the best possible color balance for each photograph, based on your own personal preferences. From top to bottom, the color dimensions are red, green, blue, brightness, and contrast. Thumbnails on the right increase each dimension, those on the left decrease each dimension. The *Large/Small* Button determines the degree of color change that results from one mouse-click on a thumbnail. *Reset* will return the photograph to its original appearance, meaning all of your edits will be erased. *Undo* will erase only the last edit you made, leaving all other edits intact. *Display Original* will show you the photo as it appeared before you made any edits. *Done* will save any edits you have made and move to the next screen. Once you select *Done* you cannot go back. Do you have any questions?

Before you enter your rating for this photograph, look at the photo for 1 minute to allow your eyes to adjust to the monitor. I will let you know when the minute has passed. ... When you reach the gray screen, open the door and I will set the computer up for the next set of trials. If you have any questions or problems please call or page me. OK you may proceed.

Figure D4: Primary Study Instructions - Session Four

Welcome to your final visit. In this session, you will view all of the photographs you edited on your last two visits and evaluate them in three ways. First, I would like you to go through the photographs and rate them for color quality based on your imagined reference photograph. Next, you will repeat the color quality ratings using a reference photograph different than your imagined reference. Finally, I will group the photos by scene and ask you to rank each photo from most preferred to least preferred. Please keep in mind that many of the photographs may appear the same, but most are in fact different from one another.

TASK 1

For the first rating scenario I would like you to use your imagined reference photograph which you described as [READ PARTICIPANT'S DESCRIPTION OF IMAGINED REFERENCE]. This photo was selected based on your definition of color quality [READ PARTICIPANT'S CQ DEFINITION]. As you view each photograph, your color quality ratings should be based on these two items alone. Please try to ignore such factors as improper exposure, poor flash range, dirt, graininess, etc. Instead, focus on whether or not the color quality of the photograph is [REREAD PARTICIPANT'S CQ DEFINITION]. Then assign each photograph a rating based on its color appearance compared to the color appearance of your imagined reference. Keep two questions in mind (1) Does the photo differ from your imagined reference? And (2) if so, by how much? Use your answers to select a color quality rating. Use any whole number from zero on up. Keep in mind that zero should represent a condition where there is no color at all on the photograph, like a solid gray field. Remember to assign your ratings based only on your imagined reference rather than any photos you have previously viewed. Please handle only one photo at a time taking care to rate them in the order they are arranged. Speak each rating aloud to me then turn the photograph face down on the desktop. Occasionally I will ask you to read the red number from the back of the photograph, after you give me your rating. Do you have any questions?

TASK 2

The last task is for you to rank order your preference for all variations of the same scene. I would like you to take the following group of photographs, spread them out on the table, then rank them from most preferred to least preferred. Your preference judgments should be based only on color balance. Place the photo you find most appealing in terms of color balance at the upper left corner. Find the photo you find next most appealing and place it to the right of the first photo. Proceed in this manner until you have placed the photo you find least appealing in the lower left corner. You will repeat this task for each scene. Do you have any questions? ... Now look through the ordering you have generated for this scene. Is there a point where the color quality of the photographs becomes unacceptable? If so, place a post-it on the first photo you consider unacceptable. So everything from this point to the left has unacceptable color balance? OR So every photograph has acceptable color balance?

APPENDIX E

Kodak Image Evaluation Program (IEP) Background

Each roll of processed participant film was evaluated by an IEP judge. The goal for this activity was to select the three highest quality first-party photographs for inclusion in the study. As a first step, the judge sorted through each participants' photographs removing everythingwith an obvious problem. The remaining photographs were pared down by visual inspection to the three of highest overall image quality. A subjective overall image quality (Q_a) rating was then given to each of these photographs (Table F1).

Q_a is a subjective measure of overall image quality. Q_a is assessed using a standards board that contains a range of consumer-type photographs varying from multiple problems to no problems. A blank frame (no image at all in the print) is assigned a value of "0" (zero). Higher Q_a values are assigned to images with higher picture quality (i.e, fewer or less extreme problems). A ratio approach is used such that a photograph that is twice as good as another is given a Q_a value that is twice as large. There is no upper limit to the Q_a scale.

The following instructions were given to the IEP judge:

- Please wear gloves while handling the images
- Keep each participant's images separate from the others
- Sort through each participant's pictures and remove all problem pictures
- From the remaining pictures choose the three best quality images. If there are not three images remaining after problems are removed, then select the highest quality problem image.
- Provide a Q_a rating for these three images
- If there is a tie, or large number of high Q_a images, choose one that contains skintones, an outdoor scene, or memory colors

Table E1: Summary of participant images

Partici-pant	Image 1	Q_a 1	Image 2	Q_a 2	Image 3	Q_a 3	Problems
1	boy in locker room	106	boy on bench-drinking	110	hockey team at rink	104	(3) boy in bkrd had red-eye
2	man at keyboard	70	field of farmland	66	colorful sky at dusk	65	(1) flash shadow (3) under/scene factor and grain
4	boy on stairs	89	3 women on couch	86	woman gift by xmas tree	84	(1) flash shadow
5	baby with blocks and woman	110	baby with sweater over head	113	grandma reading book to kids on couch	97	(3) dark background
6	desert golf course	130	2 adults and baby on patio	116	woman holding baby on giant sundial	113	
7	woman by flubber sign	106	woman looking at photo album	104	baby in high chair and girl next to her	98	

Partici-pant	Image 1	Q_a 1	Image 2	Q_a 2	Image 3	Q_a 3	Problems
8	girl on chair with coin collection	110	boy holding legos by xmas tree	106	girls opening gifts by xmas tree	89	
9	woman standing infront of TV	93	two women on couch	89	1 man 3 women dancing xmas tree in bkgd	83	(2 & 3) red-eye
10	kids playing football in snow	86	boy standing by boat, snow scene	80	boy on boat, snow scene	72	(1) color / vignette (2) vignette / oth. sharpness (3) vignette / oth. sharpness
11	two men with santa hat	123	baby opening xmas gifts	110	cat on pink rug	92	
12	woman and child by xmans tree	135	plate of cookies for Santa on hearth	128	boy by xmas tree	110	
13	man in bowling alley	89	boy in snow	73	family on couch	66	(1) flash reflection / dark bkgd / translation (2) color (3) redeye / depth of field under
14	baby girl on couch	97	man on couch with paper	96	xmas tree	76	(3) is soft on one side
15	house with snow cover	72	green walled bedroom	70	cat on couch	66	(1) color slightly blue (3) dark bkgd
16	xmas tree	123	woman putting	103	couple at tee box	89	
17	xmas decorations on mantle	116	kids playing football in snow	100	woman at dish washer	96	(1) tilt (3) shadow
18	man with camera	106	family in front of xmas tree	100	man and woman in car	103	(1) flash shadow (2 & 3) reflection
19	xmas tree	84	woman infront of xmas tree	78	man and woman in large chair	76	(2) red-eye
20	3 kids & teddy bear by xmas tree	130	closeup of baby in crib	116	baby in crib	93	
21	man in living room	103	Girl at table with a coke	84	boy at table playing peekabo	83	(1) dark bkgd (2) other (3) shadow / dark bkgd / flash reflection
22	grandfather clock	83	lady with 2 dogs in kitchen	71	dog with treat in kitchen	66	(1) scratch and color (3) shadow
24	man installing wall light	106	man with gifts	89	squirrel in birdfeeder	72	(1) shadow (2) shadow / tilt / other (3) under exposed

APPENDIX F

Monitor Calibration Data

Two Sony 17SEII 17" digital displays were selected for this study. These displays have a built in EEPROM pre-loaded with factory calibrated color temperatures of 5000K, D6500K, and 9300K. In order to adjust these monitors in the field, Sony provides field engineers with a software tool, called "DAS" (Digital Alignment Software) Numerous versions of DAS exist for Sony's extensive product line. Kodak also uses DAS to calibrate displays to our own specifications. DAS is a menu driven PC application used in conjunction with a colorimeter will allow calibration of the display. DAS prompts the user to display various test patterns on the display, thus using a colorimeter, luminance and chromaticity are optimized to aim white points. In most cases, enough range is provided in the adjustment to allow for variations from the Sony specifications. The calibration contents may also be saved to the PC as a file.

The DAS does not allow access to all 255 registers for brightness and contrast adjustments. Luminance levels required to achieve gammas ranging from 1.0 to 3.0 were out of range in some cases for the display. It was therefore necessary to utilize the front panel user controls of contrast and brightness. The 17seII monitors have screen controls or "pop-up windows" with adjustment increments from 1-100 units for contrast and brightness control. Thus an iterative procedure was used to achieve the desired gamma.

The luminance level was held at 27footlamberts (fl) on a 255 dac window signal while the brightness on a 10 dac window signal was varied. Verification measurements are then made at 17 points along the luminance scale. The luminance responses are plotted log-log then best fit using a second-order polynomial function. When the desired gamma is achieved, the corresponding brightness unit is recorded for use during the study. Resetting brightness units for different gamma positions proved to be repeatable in terms of luminance measured.

The study consisted of a total of 15 different calibration positions varying from 4061K to 14539K, with gammas ranging from 1.0 to 3.0. Five files (3 calibrations / file) were created using the DAS. The multiple calibration files were created prior to the study and saved on the PC for downloading to the display, as needed during the study. The files downloaded to the display contain parameters for image geometry, size, position, color temperature, luminance and dynamic range. The desired calibration positions are listed in Tables E1 and E2.

Table F1: Monitor I Calibration Data

	Aim Setting			**Achieved Setting**			
Treatment	x	y	gamma	x	y	gamma	luminance
1	0.3125	0.3307	1.46	0.3125	0.3313	1.49	27.0
2	0.3145	0.3168	1.46	0.3104	0.3148	1.49	27.1
3	0.2682	0.2820	1.46	0.2694	0.2810	1.49	27.1
4	0.2746	0.2723	1.46	0.2729	0.2717	1.49	27.1
5	0.3125	0.3307	2.53	0.3136	0.3307	2.52	25.4
6	0.3145	0.3168	2.53	0.3167	0.3164	2.52	26.5
7	0.2682	0.2820	2.53	0.2693	0.2819	2.52	25.6
8	0.2746	0.2723	2.53	0.2743	0.2703	2.52	25.9
15	0.2849	0.2932	2.00	0.2862	0.2961	1.98	27.0

Note: Luminance is expressed in Foot Candles

Table F2: Monitor II Calibration Data

	Aim Setting			Achieved Setting			
Treatment	x	y	gamma	x	y	gamma	luminance
9	0.2849	0.2932	3.00	0.2852	0.2935	2.73	27.0
10	0.2849	0.2932	1.00	0.2848	0.2936	1.09	27.0
11	0.2647	0.2686	2.00	0.2651	0.2675	1.98	27.0
12	0.3778	0.3751	2.00	0.3787	0.3717	1.98	27.1
13	0.2800	0.3038	2.00	0.2803	0.3032	1.98	27.2
14	0.2895	0.2831	2.00	0.2871	0.2870	1.98	27.5
16	0.2849	0.2932	2.00	0.2845	0.2941	1.98	26.9
17	0.2849	0.2932	2.00	0.2845	0.2941	1.98	26.9

Note: Luminance is expressed in Foot Candles

Table F3: Monitor Phosphor Chromaticities

	Monitor I		Monitor II	
Phosphor	x	y	x	y
Red	0.6239	0.3440	0.6233	0.3436
Green	0.2751	0.6011	0.2769	0.6001
Blue	0.1505	0.0623	0.1502	0.0645

APPENDIX G

Participant Imagined Reference Data

Table G1: Color Quality Definitions & Imagined Reference Photograph Descriptions

Parti-cipant	Personal definition of color quality	Description of imagined reference photograph	What participant liked about the colors in the photograph
1	Vivid color. Contrast between similar colors. Are the colors what they should actually be. Realistic flesh tones.	Group of people in red shirts at an outdoor arena. People are in the act of sitting/standing to cheer.	All the reds of the shirt were vivid, did not blend together. And the purity of the skintones made you feel like you were there.
2	A good neutral skiin tone and colors in balance: r=g=b about the same maximum and minimum saturation.	A buiding in Mexico set against a sky background.	Rich blue sky and bright white trim on building.
3	Saturation, brightness, sharpness, perceived color reproduction (e.g., the orange color I think when I see an orange). Overall balance of the print.	The grand canyon set against a blue sky.	Sharpness, brightness, comfortable and real feeling. I felt like the scene is right in front of me (colro jumps out of it).
4	Accuracy to actual color of subject matter. Saturated colors. Ability to differentiate various hues of a color.	A group of statues in a scene depicting the days of Caeser, in Las Vegas, NV. Under an open sky.	Sky colors very realistic. Statue colors also very accurate.
5	I do not like "hot" colors, colors that seem saturated or surreal. I am influenced by how sharp the picture is. I look at faces and can easily see if the whites have a green or blue tint to them. I like to see sharp edges versus colors that blend into each other.	Colorful ballons of all shapes and sizes rising into the air at the Albuquerque balloon festival.	Brilliant sharp colors against a morning blue sky. Picture was exactly how I remembered event. Brought back vivid memories.
6	Lighting conditions. Brightness of colors. Reality of colors.	Hawaiin golf course on ocean.	Deep blue background and green foreground.
7	Accuracy of color reproduction (i.e., does the orange blouse in the picture match the actual blouse.)	Cat and dog sitting on a couch in a living room.	Accurate.
8	Saturation, natural looking skin tones. White whites, not yellow or cyan. Overall balance of primary colors in an image, considering the scene.	Picinic scene with four people at a table with red and white checkered table cloth and food wrappers. grass, blue sky, pine trees in background.	The colors were bright, vivid and smooth in places of low frequency, and the skin tones looked realistic.
9	The best approximation to colors in the real world.	Building on a college campus with a statue in the foreground.	Good representation of shadows. The scene looked natural and demonstrated that the picture was taken in the late afternoon.
10	The degree to which the color in the photo reproduces the original scene in the viewer's eye.	A strikeout scene from a baseball game. pitched ball just missing bat as batter was swinging.	Bright colors and action shot with minimal background.
11	Contrast, brightness, definition, background, sharpness, clear.	Large, beautiful rock in a riverbed, with trees, water, and hillside.	They were bright, true colors. Sun was shinning, picture was clear and sharp. Picture captured every detail to its fullest.
12	Accurate balance and hue with good saturation and appropriate brightness.	Bride and groom in a park with green grass and fall foliage.	Sharp, accurate foliage, green grass, clothing, and skin colors.
13	Contrast, depth, tone, brightness.	Three children on an overturned tree in a wooded area.	Contrast between shadows and lights. Backlighting and contrast make the photo unique.

Partici-pant	Personal definition of color quality	Description of imagined reference photograph	What participant liked about the colors in the photograph
14	The ability of a film or photographic media to reproduce "live" colors (i.e., reproduce color the way they look, not saturating or altering their hue).	A couple, indoors at a wedding reception.	It looked real.
15	Reasonably accurate reproduction of original color: blance, level (intensity), brightness, and contrast, good black, good white, no unforseen color bias.	Cliff face at Bandolier National Monument in New Mexico. Framed by green tree in foreground and sky in background.	Saturated, contrasty, and "crisp".
16	Realistic reproduction of hue. Relatively high saturation without sacrifice of detail. Strong color detail reproduction.	New Mexico desert bluffs in summer. Strong red rock formations under bright blue sky and white clouds.	All were bright and contrasted against one another, but desert detail was also well maintained. Realistic reproduction of a scene I remembered well.
17	How realistic the colors are.	A log cabin in the woods set against a blue sky. There is snow on the ground , trees, and part of the roof. Some of the red roof is exposed.	Liked the image because of its composition and the memories it brought back.
18	Correct tonescale--people lok correct but with a fairly high saturation in the other colors in the scene.	Two red birds hanging off a snow covered limb in the forest.	Everything in the photo was a shade of gray or white, except for the birds.
19	Colors look realistic (from memory).	Two skiers on a Utah mountain overlooking a scenic view. Sunny day.	The sky was beautiful blue but realistic. Bright colors of ski clothes were realistic.
20	Sharpness, grain, contrast, lighting in the scene. high contrast, good rendition of skin tones.	Two young children sitting on the floor of a family room.	Skin tone was rendered perfectly.
21	Accuracy of reproduction with respect to scene. Range of color. Sensitivity to variations in light.	Sunset in Pheonix, AZ. Street level picture with cars, buildings, palm trees, and evening sky.	Vibrant. The picture is like what I saw. Good range of color.
22	Rich vibrant colors that appear like the real life colors.	Colorado mountain range framed by trees on both sides.	They were very realistic, looked like the actual scene.
24	White whites. Bright vivid colors. The picture is like I remembered it.	Cindarellas castle at Disney World. People mingling in the foreground, sky and clouds in the background.	Castle was pink, sky was very blue that day. Person had a white shirt on that day so color balance was good.

APPENDIX H

Coded Analysis Summary Information

This appendix presents tables of mean and empirical values. Means, standard errors, and sample sizes are based on transformed data prior to averaging over participants and scenes. Empirical values are based on the response surface regressions run on the averaged data in coded form. Empirical values for each factor were determined with all other factors held at their 0 level (i.e., gamma at 2.0, purity at 0, color temperature at 9300K). Two sets of tables are found for each dependent measure; one set describing first-party data and a second set describing third-party data.

TABLE H1: MEAN FIRST-PARTY SOFTCOPY COLOR QUALITY RATINGS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	132	148	163	166	173	165	157	158	157	164	156	159	160	155	164
SE	2.90	1.59	1.14	1.64	3.24	1.73	1.63	1.50	1.79	2.47	2.83	1.70	1.45	1.72	2.21
N	66	260	323	260	66	66	260	323	260	66	66	260	329	260	60

TABLE H2: EMPIRICAL FIRST-PARTY SOFTCOPY COLOR QUALITY RATINGS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	133	150	163	170	170	164	164	163	163	163	159	162	163	162	158
SE	3.73	3.39	4.42	3.39	3.73	3.73	3.39	4.42	3.39	3.73	3.73	3.39	4.42	3.39	3.73

TABLE H3: MEAN THIRD-PARTY SOFTCOPY COLOR QUALITY RATINGS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	136	158	166	172	173	173	167	160	163	167	152	163	164	167	169
SE	3.68	1.59	1.35	1.61	2.74	3.36	1.69	1.55	1.62	2.61	3.17	1.53	1.58	1.77	2.12
N	66	264	322	264	66	66	264	322	264	66	64	264	330	264	60

TABLE H4: EMPIRICAL THIRD-PARTY SOFTCOPY COLOR QUALITY RATINGS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	140	158	171	175	171	175	173	171	169	168	155	165	171	172	168
SE	2.95	2.68	3.50	2.68	2.95	2.95	2.68	3.50	2.68	2.95	2.95	2.68	3.50	2.68	2.95

TABLE H5: MEAN FIRST-PARTY HARDCOPY COLOR QUALITY RATINGS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	146	159	164	169	170	167	165	161	163	160	157	164	162	164	169
SE	4.24	2.03	2.01	2.22	4.05	4.65	2.17	2.07	2.13	3.36	5.32	2.04	1.90	2.26	4.47
N	66	260	323	260	66	66	260	323	260	66	66	260	329	260	60

TABLE H6: EMPIRICAL FIRST-PARTY HARDCOPY COLOR QUALITY RATINGS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	149	159	167	170	169	167	168	167	165	162	161	165	167	165	162
SE	2.93	2.66	3.47	2.66	2.93	2.93	2.66	3.47	2.66	2.93	2.93	2.66	3.47	2.66	2.93

TABLE H7: MEAN THIRD-PARTY HARDCOPY COLOR QUALITY RATINGS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	114	138	145	154	154	146	147	140	145	144	148	148	140	144	141
SE	4.76	2.62	1.93	2.18	3.54	3.56	2.49	2.12	2.43	4.27	5.68	2.53	1.98	2.39	3.73
N	66	264	322	264	66	66	264	322	264	66	64	264	330	264	60

TABLE H8: EMPIRICAL THIRD-PARTY HARDCOPY COLOR QUALITY RATINGS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	119	134	147	153	154	149	148	147	146	146	151	149	147	145	143
SE	3.67	3.33	4.35	3.33	3.67	3.67	3.33	4.35	3.33	3.67	3.67	3.33	4.35	3.33	3.67

TABLE H9: MEAN FIRST-PARTY HARDCOPY REJECTION PROPORTIONS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	0.59	0.33	0.25	0.19	0.11	0.21	0.27	0.29	0.26	0.27	0.32	0.23	0.28	0.30	0.20
SE	0.05	0.02	0.02	0.02	0.03	0.04	0.03	0.04	0.02	0.04	0.05	0.02	0.04	0.03	0.04
N	6	24	30	24	6	6	24	30	24	6	6	24	30	24	6

TABLE H10: EMPIRICAL FIRST-PARTY HARDCOPY REJECTION PROPORTIONS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	0.53	0.36	0.22	0.16	0.16	0.23	0.22	0.22	0.23	0.24	0.25	0.23	0.22	0.24	0.26
SE	0.08	0.07	0.09	0.07	0.08	0.08	0.07	0.09	0.07	0.08	0.08	0.07	0.09	0.07	0.08

TABLE H11: MEAN THIRD-PARTY HARDCOPY REJECTION PROPORTIONS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	0.76	0.49	0.34	0.21	0.26	0.33	0.31	0.41	0.39	0.33	0.31	0.31	0.39	0.38	0.43
SE	0.08	0.03	0.02	0.03	0.05	0.06	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.07
N	6	24	30	24	6	6	24	30	24	6	6	24	30	24	6

TABLE H12: EMPIRICAL THIRD-PARTY HARDCOPY REJECTION PROPORTIONS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	0.74	0.47	0.27	0.20	0.23	0.27	0.26	0.27	0.30	0.35	0.29	0.26	0.27	0.33	0.41
SE	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.05	0.04	0.04

TABLE H13: MEAN FIRST-PARTY RED EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	2.87	0.19	0.56	0.46	-.38	0.68	-0.87	-0.02	1.52	4.62	-5.30	-0.88	1.76	1.54	1.92
SE	1.02	0.56	0.57	0.63	0.96	1.13	0.54	0.52	0.64	1.37	1.27	0.60	0.52	0.58	0.97
N	66	260	323	260	66	66	260	323	260	66	66	260	329	260	60

TABLE H14: EMPIRICAL FIRST-PARTY RED EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	1.64	1.17	0.76	0.50	0.39	0.30	0.11	0.76	2.36	4.52	-4.83	-1.55	0.76	1.54	0.96
SE	0.99	0.90	1.17	0.90	0.99	0.99	0.90	1.17	0.90	0.99	0.99	0.90	1.17	0.90	0.99

TABLE H15: MEAN THIRD-PARTY RED EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	-0.38	-1.40	-2.56	-2.35	-0.91	-2.12	-2.56	-2.45	-1.19	0.30	-8.05	-2.88	-0.92	-0.87	-1.50
SE	1.29	0.69	0.62	0.67	1.01	1.28	0.68	0.59	0.68	1.32	1.38	0.65	0.57	0.70	1.19
N	66	264	322	264	66	66	264	322	264	66	64	264	330	264	60

TABLE H16: EMPIRICAL THIRD-PARTY RED EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	0.03	-0.87	-1.44	-1.51	-1.16	-2.08	-1.93	-1.44	-0.60	0.42	-7.22	-3.72	-1.44	-1.02	-2.17
SE	0.97	0.88	1.15	0.88	0.97	0.97	0.88	1.15	0.88	0.97	0.97	0.88	1.15	0.88	0.97

TABLE H17: MEAN FIRST-PARTY GREEN EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	1.06	1.62	1.01	1.42	0.68	1.29	1.77	0.85	1.27	1.21	0.15	1.08	0.99	1.96	1.75
SE	0.68	0.38	0.30	0.40	0.36	0.67	0.43	0.27	0.35	0.81	0.49	0.33	0.28	0.45	0.86
N	66	260	323	260	66	66	260	323	260	66	66	260	329	260	60

TABLE H18: EMPIRICAL FIRST-PARTY GREEN EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	1.34	1.13	0.98	0.93	0.98	1.81	1.28	0.98	1.00	1.27	0.43	0.62	0.98	1.49	2.05
SE	0.49	0.44	0.58	0.44	0.49	0.49	0.44	0.58	0.44	0.49	0.49	0.44	0.58	0.44	0.49

TABLE H19: MEAN THIRD-PARTY GREEN EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	0.68	0.87	0.54	1.02	0.15	0.91	1.00	0.50	0.89	0.15	0.31	0.85	0.55	1.04	0.50
SE	1.17	0.48	0.37	0.45	0.61	0.76	0.48	0.40	0.45	0.79	0.99	0.49	0.38	0.44	0.81
N	66	264	322	264	66	66	264	322	264	66	64	264	330	264	60

TABLE H20: EMPIRICAL THIRD-PARTY GREEN EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	0.70	0.97	1.07	0.92	0.60	1.00	1.10	1.07	0.86	0.53	0.50	0.87	1.07	1.02	0.78
SE	0.41	0.37	0.49	0.37	0.41	0.41	0.37	0.49	0.37	0.41	0.41	0.37	0.49	0.37	0.41

TABLE H21: MEAN FIRST-PARTY BLUE EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	-1.89	0.25	0.12	-0.42	-0.83	-2.35	-0.42	0.34	0.25	-1.44	7.35	0.54	-1.52	-0.71	-2.08
SE	1.48	0.76	0.66	0.67	0.95	1.31	0.74	0.65	0.69	1.26	1.78	0.66	0.57	0.77	1.29
N	66	260	323	260	66	66	260	323	260	66	66	260	329	260	60

TABLE H22: EMPIRICAL FIRST-PARTY BLUE EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	-1.14	-0.98	-0.95	-1.07	-1.32	-2.31	-1.47	-0.95	-0.89	-1.21	5.59	1.62	-0.95	-1.40	-0.06
SE	1.45	1.32	1.72	1.32	1.45	1.45	1.32	1.72	1.32	1.45	1.45	1.32	1.72	1.32	1.45

TABLE H23: MEAN THIRD-PARTY BLUE EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	6.97	9.13	9.01	7.88	6.44	5.68	7.27	9.07	9.73	7.42	17.97	10.38	6.76	6.63	6.75
SE	1.48	0.71	0.65	0.64	0.94	1.05	0.66	0.67	0.68	1.13	2.00	0.70	0.52	0.63	1.15
N	66	264	322	264	66	66	264	322	264	66	64	264	330	264	60

TABLE H24: EMPIRICAL THIRD-PARTY BLUE EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	7.53	7.59	7.35	6.79	6.03	4.99	6.27	7.35	8.02	8.26	16.93	11.20	7.35	6.40	7.95
SE	1.03	0.93	1.22	0.93	1.03	1.03	0.93	1.22	0.93	1.03	1.03	0.93	1.22	0.93	1.03

TABLE H25: MEAN FIRST-PARTY BRIGHTNESS EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	3.26	7.62	8.36	10.75	8.11	8.11	8.71	7.59	9.65	7.05	8.26	9.67	7.72	8.69	6.08
SE	2.18	0.88	0.69	0.89	1.33	1.46	0.91	0.77	0.86	1.39	1.27	0.88	0.77	0.90	1.53
N	66	260	323	260	66	66	260	323	260	66	66	260	329	260	60

TABLE H26: EMPIRICAL FIRST-PARTY BRIGHTNESS EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	3.84	9.72	13.01	12.60	9.24	8.21	11.59	13.01	11.82	8.66	9.03	12.12	13.01	11.06	7.03
SE	1.30	1.18	1.54	1.18	1.30	1.30	1.18	1.54	1.18	1.30	1.30	1.18	1.54	1.18	1.30

TABLE H27: MEAN THIRD-PARTY BRIGHTNESS EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	-1.21	1.72	3.31	5.00	3.94	3.33	3.24	2.62	3.48	2.73	3.36	4.13	2.39	2.59	4.00
SE	1.70	0.75	0.59	0.67	1.28	1.20	0.71	0.64	0.73	1.39	1.27	0.69	0.63	0.74	1.41
N	66	264	322	264	66	66	264	322	264	66	64	264	330	264	60

TABLE H28: EMPIRICAL THIRD-PARTY BRIGHTNESS EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	-1.15	1.47	3.50	4.50	4.52	3.37	3.47	3.50	3.45	3.33	4.62	3.97	3.50	3.31	3.38
SE	0.85	0.77	1.01	0.77	0.85	0.85	0.77	1.01	0.77	0.85	0.85	0.77	1.01	0.77	0.85

TABLE H29: MEAN FIRST-PARTY CONTRAST EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	51.82	26.06	17.34	7.67	4.55	17.50	16.92	21.38	16.81	19.09	15.23	15.29	21.88	18.44	18.58
SE	3.13	1.48	0.94	1.12	1.76	2.01	1.41	1.37	1.46	2.08	1.99	1.40	1.35	1.46	1.98
N	66	260	323	260	66	66	260	323	260	66	66	260	329	260	60

TABLE H30: EMPIRICAL FIRST-PARTY CONTRAST EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	46.47	28.64	14.47	7.04	6.07	16.07	14.85	14.47	15.18	16.70	12.64	13.36	14.47	15.88	17.35
SE	3.54	3.21	4.19	3.21	3.54	3.54	3.21	4.19	3.21	3.54	3.54	3.21	4.19	3.21	3.54

TABLE H31: MEAN THIRD-PARTY CONTRAST EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
mean	52.27	29.13	21.44	11.88	11.67	21.97	20.06	25.50	20.95	22.20	20.55	19.34	25.52	21.67	23.17
SE	2.88	1.50	1.05	0.94	1.82	2.21	1.43	1.34	1.30	2.20	2.52	1.32	1.31	1.40	2.02
N	66	264	322	264	66	66	264	322	264	66	64	264	330	264	60s

TABLE H32: EMPIRICAL THIRD-PARTY CONTRAST EDITS FOR GAMMA, PURITY AND COLOR TEMPERATURE

	Gamma					**Purity**					**Color Temperature**				
	1.0	1.46	2.0	2.53	3.0	-12	-6	0	+6	+12	4K	6K	9K	12K	14K
Emp.	47.94	30.59	17.35	11.26	11.77	19.47	17.83	17.35	18.37	20.47	17.97	17.09	17.35	18.98	21.52
SE	3.23	2.93	3.83	2.93	3.23	3.23	2.93	3.83	2.93	3.23	3.23	2.93	3.83	2.93	3.23

APPENDIX I

Reduced Regression Models

This appendix presents results from regression analyses based on reduced models. Each analysis presented in the **Results** section was restructured to include only those parameters deemed to represent statistically significant and practically meaningful differences.

Softcopy Color Quality (SCQ)

First-Party

SCQ = 161.39 + 9.88 gamma – 2.95 gamma^2				
R^2 = 0.91		RMSE = 3.61		
Term	Estimate	SE	T ratio	P
Intercept	161.39	1.27	126.95	< 0.0001
Gamma	9.88	0.93	10.59	< 0.0001
Gamma^2	-2.95	0.86	-3.41	0.0051

Third-Party

SCQ = 171.19 + 8.35 gamma + 3.40 Temperature – 4.48 gamma^2 + 1.03 Temperature x Gamma – 2.73 Temperature^2				
R^2 = 0.93		RMSE = 3.60		
Term	Estimate	SE	T ratio	P
Intercept	171.19	1.82	93.86	< 0.0001
Gamma	8.35	0.93	8.99	< 0.0001
Temperature	3.40	0.93	3.66	0.0053
Gamma^2	-4.48	0.94	-4.78	0.0010
Temperature x Gamma	1.03	1.27	0.81	0.4406
Temperature^2	-2.73	0.94	-2.91	0.0173

Red Edits

First-Party

Red = 0.93 + 1.13 Purity + 1.55 Temperature + 0.42 $Purity^2$ + 0.50 Temperature x Purity – 0.82 $Temperature^2$				
R^2 = 0.87		RMSE = 1.11		
Term	Estimate	SE	T ratio	P
Intercept	0.93	0.56	1.65	0.1328
Purity	1.13	0.29	3.94	0.0034
Temperature	1.55	0.29	5.41	0.0004
$Purity^2$	0.42	0.29	1.47	0.1760
Temperature x Purity	0.50	0.39	1.28	0.2337
$Temperature^2$	-0.82	0.29	-2.83	0.0198

Third-Party

Red = –0.85 + 1.35 Temperature – 1.10 $Temperature^2$				
R^2 = 0.72		RMSE = 1.27		
Term	Estimate	SE	T ratio	P
Intercept	-0.85	0.45	-1.90	0.0821
Temperature	1.35	0.33	4.13	0.0014
$Temperature^2$	-1.10	0.30	-3.63	0.0034

Green Edits

First-Party

Green = 1.28 + 0.44 Temperature – 0.01 $Temperature^2$				
R^2 = 0.37		RMSE = 0.63		
Term	Estimate	SE	T ratio	P
Intercept	1.28	0.22	5.76	< 0.0001
Temperature	0.44	0.16	2.68	0.0201
$Temperature^2$	-0.01	0.15	-0.07	0.9463

Blue Edits

First-Party

Blue = – 1.39 – 1.51 Temperature + 1.19 Temperature^2				
R^2 = 0.74		RMSE = 1.30		
Term	Estimate	SE	T ratio	P
Intercept	-1.39	0.46	-3.04	0.0104
Temperature	-1.51	0.34	-4.50	0.0007
Temperature^2	1.19	0.31	3.82	0.0024

Third-Party

Blue = 6.83 – 2.40 Temperature + 1.60 Temperature^2				
R^2 = 0.85		RMSE = 1.39		
Term	Estimate	SE	T ratio	P
Intercept	6.83	0.49	13.97	< 0.0001
Temperature	-2.40	0.36	-6.68	< 0.0001
Temperature^2	1.60	0.33	4.82	0.0004

Brightness Edits

First-Party

Brightness = 9.19 + 1.44 gamma – 0.76 gamma^2				
R^2 = 0.43		RMSE = 2.12		
Term	Estimate	SE	T ratio	P
Intercept	9.19	0.75	12.31	< 0.0001
Gamma	1.44	0.55	2.63	0.0220
Gamma^2	-0.76	0.51	-1.49	0.1616

Third-Party

Brightness = 3.64 + 1.52 gamma – 0.56 gamma^2				
R^2 = 0.74		RMSE = 1.09		
Term	Estimate	SE	T ratio	P
Intercept	3.64	0.38	9.49	< 0.0001
Gamma	1.52	0.28	5.38	0.0002
Gamma^2	-0.56	0.26	-2.14	0.0533

Contrast Edits

First-Party

Contrast = 15.45 – 10.80 gamma + 3.09 gamma^2				
R^2 = 0.94		RMSE = 3.23		
Term	Estimate	SE	T ratio	P
Intercept	15.45	1.14	13.61	< 0.0001
Gamma	-10.80	0.83	-12.96	< 0.0001
Gamma^2	3.09	0.77	4.01	0.0017

Third-Party

Contrast = 19.36 – 9.66 gamma + 3.00 gamma^2				
R^2 = 0.93		RMSE = 3.06		
Term	Estimate	SE	T ratio	P
Intercept	9.36	1.08	17.95	< 0.0001
Gamma	-9.66	0.79	-12.22	< 0.0001
Gamma^2	3.00	0.73	4.10	0.0015

Hardcopy Color Quality

First-Party

HCQ = 164.79 + 5.51 gamma – 1.69 gamma^2				
R^2 = 0.69		RMSE = 4.36		
Term	Estimate	SE	T ratio	P
Intercept	164.79	1.53	107.50	< 0.0001
Gamma	5.51	1.12	4.90	0.0004
Gamma^2	-1.69	1.04	-1.62	0.1309

Third-Party

HCQ = 147.14 + 9.26 gamma – 2.12 Temperature – 3.09 gamma^2 – 0.48 Temperature x Gamma – 0.07 Temperature^2				
R^2 = 0.92		RMSE = 3.71		
Term	Estimate	SE	T ratio	P
Intercept	147.14	1.88	78.32	< 0.0001
Gamma	9.26	0.96	9.68	< 0.0001
Temperature	-2.12	0.96	-2.22	0.0538
Gamma^2	-3.09	0.97	-3.20	0.0109
Temperature x Gamma	-0.48	1.31	-0.36	0.7246
Temperature^2	-0.07	0.97	-0.07	0.9463

Hardcopy Rejection Rates (HRR)

First-Party

HRR = 0.24 – 0.10 gamma + 0.03 gamma^2				
R^2 = 0.76		RMSE = 0.07		
Term	Estimate	SE	T ratio	P
Intercept	0.24	0.02	10.51	< 0.0001
Gamma	-0.10	0.02	-5.87	< 0.0001
Gamma^2	0.03	0.02	1.91	0.0800

Third-Party

HRR = 0.30 – 0.14 gamma + 0.03 Temperature + 0.06 gamma^2 + 0.01 Temperature x Gamma + 0.02 Temperature^2				
R^2 = 0.94		RMSE = 0.05		
Term	Estimate	SE	T ratio	P
Intercept	0.30	0.03	11.84	< 0.0001
Gamma	-0.14	0.01	-10.70	< 0.0001
Temperature	0.03	0.01	2.59	0.0294
Gamma^2	0.06	0.01	4.29	0.0020
Temperature x Gamma	0.01	0.02	0.36	0.7825
Temperature^2	0.02	0.01	1.18	0.2668

VITA

Wende L. Dewing was born July 26, 1967 in Minneapolis, Minnesota. In 1989, she received a B.A. in mathematics, with a minor in studio arts, from Macalester College in St. Paul, Minnesota. Wende began her graduate studies in 1992 at the University of Minnesota, Twin Cities Campus. For the next three years, she conducted research in the areas of driver behavior and Intelligent Transportation Systems (ITS), through the University's Human Factors Research Laboratory. She studied the factors influencing drivers' left-turn decisions, how the content and structure of traffic advisories affects route planning, and the effects of multi-tasking on driver performance. In addition, she worked as a student with the Honeywell Technology Center, in Minneapolis, to develop interface design guidelines for Automated Highway Systems (AHS). Wende graduated from the University with a Masters of Science degree in Industrial Engineering and Operations Research in 1995. Later that year, she entered a Doctorate program at Virginia Polytechnic Institute and State University (a.k.a., Virginia Tech), in Blacksburg, Virginia. There, she conducted research in the areas of pyschophysics and image quality through the Displays and Controls Laboratory. Her projects employed subjective, psychophysical, photometric, and radiometric display evaluation techniques for commercial and consumer applications. Wende's doctoral research was funded by Eastman Kodak Company of Rochester, New York. During her three-year internship with Kodak, she researched the effects of cathode-ray tube (CRT) color balance on soft-copy hard-copy matching and developed a web-based tool for visual characterization of CRT displays. Wende received her Ph.D. in Industrial and Systems Engineering, with an emphasis in Human Factors, in 1999. She is a member of the Human Factors and Ergonomics Society and the Society for Information Display. Wende has accepted a position with the Honeywell Technology Center in Minneapolis where she will conduct research on information and decision technology for aviation, process control, home, and commercial building environments. A sample of her publications follows:

Dewing, Wende (Oct 1999). Softcopy image manipulation and its influence on perceived color quality of printed output. Proceedings of the Human Factors and Ergonomics Society 43rd annual meeting. Houston, TX.

Levitan, L., Burus, M., Dewing, W., Reinhart, W., Vora, P., and Llaneras, R. (1994). Preliminary human factors guidelines for automated highway system designers. (Contract No. DTFH61-92-C-00100). Washington, DC: Federal Highway Administration.

Dewing, W. and Stackhouse, S. (1994). Following advice from traffic advisories. (Tech. Report MN/RC-94/29). Saint Paul, MN: Minnesota Department of Transportation.

Hancock, P.A., Dewing, W., and Parasuraman, R. (1993, April). The human factors of intelligent travel systems. *Ergonomics in Design*, 1 (2), 12-15.