Visual Calibration and Correction for Ambient Illumination

KATE DEVLIN and ALAN CHALMERS
University of Bristol
and
ERIK REINHARD
University of Bristol
University of Central Florida

Many applications require that an image will appear the same regardless of where or how it is displayed. However, the conditions in which an image is displayed can adversely affect its appearance. Computer monitor screens not only emit light, but can also reflect extraneous light present in the viewing environment. This can cause images displayed on a monitor to appear faded by reducing their perceived contrast. Current approaches to this problem involve measuring this ambient illumination with specialized hardware and then altering the display device or changing the viewing conditions. This is not only impractical, but also costly and time consuming. For a user who does not have the equipment, expertise, or budget to control these facets, a practical alternative is sought. This paper presents a method whereby the display device itself can be used to determine the effect of ambient light on perceived contrast, thus enabling the viewers themselves to perform visual calibration. This method is grounded in established psychophysical experimentation and we present both an extensive procedure and an equivalent rapid procedure. Our work is extended by providing a novel method of contrast correction so that the contrast of an image viewed in bright conditions can be corrected to appear the same as an image viewed in a darkened room. This is verified through formal validation. These methods are easy to apply in practical settings, while accurate enough to be useful.

Categories and Subject Descriptors: I.3.3 [**Computer Graphics**]: Picture/image generation—*Display algorithms, viewing algorithms*; I.3.6 [**Computer Graphics**]: Methodology and Techniques—*Device independence,ergonomics*

General Terms: Experimentation, Human factors, Standardization, Verification

Additional Key Words and Phrases: Viewing conditions, ambient illumination, reflections, contrast correction, perceptually accurate display, device independence, ergonomics

---

1. INTRODUCTION

Many applications that use electronic display devices require images to appear a certain way. In areas as diverse as medical imaging [Alter et al. 1982; Baxter et al. 1982; Rogers et al. 1987; National Electrical Manufacturers Association 2003], aviation [Federal Aviation Administration 2000], visualization [Ware 2000], photography [Evans 1959; Hunt 2004], and predictive lighting and realistic image synthesis [Ashdown and Frank 1995], similarity is desirable between the image as it was created and the resultant image that is viewed by the end user. The user must be confident that the image they

---

Authors' Address: Kate Devlin is currently at the Department of Computing, Goldsmiths College, University of London, New Cross, London SE14 6NW, UK. From March 2007, Alan Chalmers will be at the Warwick Digital Laboratory, Warwick Manufacturing Group, The University of Warwick, Coventry, CV4 7AL. Erik Reinhard can be contacted through the University of Bristol, Department of Computer Science, MVB, Woodland Road, Bristol BS8 1UB, UK, University of Central Florida, Oscala, Florida 32670.

are viewing is faithful to the original; they require *perceptual fidelity*. However, a given image will not always be perceived in the same way. Problems may arise because the sequence of events from image creation to perception is open to adverse influence that can result in an image that deviates from the way it was intended to look. As images are often displayed on different monitors and in different locations from where they were created (such as images displayed over a network or on the Internet), it is necessary to ensure that steps have been taken to ensure perceptual consistency, where any point in an image will look the same regardless of changes in viewing location and display device. To ensure that the scene as it was created closely resembles the scene as it is displayed, it is necessary to be aware of any factors that might adversely influence the display medium.

The image displayed on a computer monitor goes through a sequence of processing steps before it is ultimately displayed on screen. It may have to be resampled or discretized to match the resolution of the display, with antialiasing applied to avoid spatial artifacts such as jagged edges and Moiré patterns [Watt 2000]. Dynamic range reduction may be carried out to map any wide ranging luminances in an image to the limited luminance range of the display device [Tumblin and Rushmeier 1993; Ward Larson et al. 1997; DiCarlo and Wandell 2000; Devlin et al. 2002; Reinhard et al. 2005]. Following this, gamma correction may be applied to account for the nonlinear response of the electron guns [Poynton 2003] and to map luminances into a perceptually uniform domain [Wandell 1995; Poynton 1998]. The mismatch between the display environment and the environment that the image represents may affect the observer's perception of the image. This may be addressed by applying a color appearance model, such as the recently proposed CIECAM02 model [Moroney et al. 2002]. All these steps go toward preserving perceptual fidelity, i.e., to some degree the appearance of images may be kept constant across display devices and display environments. However, beyond the adjustments to the actual image, the processes that occur *after* the luminances are displayed on screen and *before* they reach the retina must also be considered. Computer monitors are self-luminous, but also reflect light, resulting in the appearance of decreased contrasts and increased luminances [Ware 2000]. This is a physical problem with a direct perceptual impact. An example of this is given in Figure 1 where the same image is shown as it appears when displayed in a room with no ambient light present (*left*) and when displayed in a room lit by a D65 light source (*right*).

While the presence of such illumination may have a detrimental effect on image appearance, many working conditions require a certain level of illumination in a room, to enable note-taking, for example. Therefore, the extraneous illumination cannot simply be removed, but rather should be accounted for in some way. Current approaches to this problem involve measuring the ambient illumination with specialized hardware such as a photometer, spectroradiometer, or illuminance meter, and altering the display device or changing the viewing conditions. However, additional hardware is an extra expense and impractical to acquire, and requires the knowledge to use it. Moreover, this equipment measures the physical value of the light present in the viewing environment rather than its perceptual impact.

For certain applications, such as trade or industry, where a direct match between a displayed design and the resulting product is essential, it is likely that a specific viewing environment exists, and full calibration of all equipment has occurred. However, there are other fields where it is not possible to guarantee the fidelity of a displayed image (such as in the use of digital image archives [Reilly and Frey 1996]). This may be because of a lack of equipment, facilities, or cost. Nonetheless, in these circumstances users may wish to ensure that they have taken any possible steps within their measure toward perceptual fidelity.

In this paper, we present a method, based on an experimental framework, whereby the display device itself can be used to estimate the level of ambient illumination affecting an image. First, we present a psychophysical study which shows that common office lighting conditions have a measurable impact on the perceived contrast of displayed images. Second, we offer a rapid experiment, which may be

Fig. 1. Example of a “washed out” image. The presence of extraneous light in the viewing environment can reduce the perceived contrast of an image (bottom) compared to an image displayed in darkness (top). For completeness, the full screen shot is shown as an inset.

performed quickly by a nonspecialist user. This technique is analogous to current methods to estimate a monitor’s gamma and does not require any equipment other than the monitor itself. We show that this technique is sufficiently accurate in characterizing a monitor’s reflective properties to be of practical use. Third, we provide a new function to remap an image’s luminance values to alter the perceived contrast, so that an image viewed in bright conditions appears the same as an image viewed in a darkened room by preserving contrast for a given value. (We note that it will be impossible to reproduce the original image exactly, as ambient lighting increases the minimum luminance on screen, and nothing darker than this new minimum luminance can be displayed.) Finally, we report an experiment that validates our results, thus confirming the utility of this approach. These methods are fast, inexpensive, and require no additional hardware. They are aimed at users who do not have traditional instrumentation to ensure accurate display, and therefore our methods can be seen as a practical compromise between a lack of display quality control and a high-cost rigidly calibrated system.

2. BACKGROUND

The average amount of light present in a room is known as the *ambient illumination* and it affects the perceived contrast of displayed images in two ways. First, the reflection of ambient illumination from the screen of a monitor affects the perceived contrast of displayed images. In addition, the image (on a computer monitor) does not fill the whole of the visual field and, as a result, visual adaptation is partly determined by the ambient illumination present [Evans 1959; Fairchild 1995].It is estimated that under normal office conditions, between 15 and 40% of illumination reaching the eye via the monitor will indirectly come from the reflection of ambient light [Ware 2000].

Correcting for reflections from computer monitors typically follows one of three approaches: the display device can be physically altered to reduce reflections; the environment can be adjusted, thereby controlling the ambient light, or the environment can be characterized and the effects of the ambient light can be taken into account when an image is displayed by applying some form of algorithmic correction.

To physically alter the display device, antiglare screens may be fitted to reduce reflections. While this changes the amount of light reflected off a screen, it does not eliminate the problem—it merely changes it in an uncalibrated manner as the amount of light reflected still depends on the (typically unknown) amount of light present in the environment. Although screen reflections may also be reduced, this can be at the expense of reduced screen brightness and resolution [Oborne 1995].

Although monitors have controls labeled “Contrast” and “Brightness,” these specify the luminance level and the black point of the monitor, respectively. The brightness control should be set so that an RGB input of [0, 0, 0] appears black (rather than dark gray), while the contrast level setting depends on preference. However, setting this excessively high can produce problems, such as sensitivity to flicker, reduced contrast as a result of light scatter, and loss of resolution [Poynton 2003]. It is, therefore, recommended that these controls are not used to reduce the effect of ambient light and should, instead, be set only once and left unchanged thereafter.

The viewing environment may be controlled to conform to known standards. The International Standards Organization (ISO) has specified a controlled viewing environment [ISO (International Standards Organisation) 2000], listing a wide range of prerequisites that should be fulfilled to achieve the best possible viewing conditions when working with images displayed on screen, thus reducing inconsistencies in image perception. For many applications, adhering to this standard is impractical as it includes designing the environment to minimize interference with the visual task and baffling extraneous light, ensuring no strongly colored surfaces (including the observer’s clothing) are present within the immediate environment, and ensuring that walls, ceiling, floors, clothes and other surfaces in the field of view are colored a neutral matt gray with a reflectance of 60% or less.

While such guidelines are a step toward a controlled viewing environment, such specific conditions are not always available, or indeed feasible. Work is often carried out in a nonspecialized office space, and this must conform to legislation on workplace conditions. Adherence to these mean that the ISO’s controlled viewing environment, described above, is far more difficult to achieve. For this reason, control of the viewing environment is often not a practical approach to controlling ambient light and is, therefore, not widely adopted.

To characterize and correct for the reflective properties of display devices, the amount of reflected light must be measured. Currently, this requires expensive and specialized equipment, such as photometers, illuminance meters, or spectroradiometers. Although no changes to the physical environment need to be made for this approach, the cost of characterizing display reflections is too high to be practical for many applications. This appears to be a major reason why it is not standard practice to routinely correct for reflections off display devices. In addition, the ability of hardware devices to measure the effect of ambient lighting is still lacking, as accurate measures can require more luminance data than is practical to collect [Tiller and Veitch 1995], or cannot be incorporated in physical measurements [Besuijen and Spenkelink 1998].

As a computer monitor does not fill the whole field of view, the illumination surrounding it will influence the state of adaptation of the observer and thus the appearance of images. This is investigated in work on brightness perception [Stevens and Stevens 1963; Bartleson and Breneman 1967] and color appearance. Color appearance models attempt to predict how colors are perceived in particular environments [Fairchild 2005]. They are useful and important tools because they aid in the preservation of color appearance across display environments. We, therefore, advocate their use alongside our work. However, color appearance models do not address the specific issue of monitor reflections.

One application area where the reflective properties of display devices adversely affect task performance is in medical imaging. Medical imaging and, in particular, radiology, requires the interpretation of images on either film or soft-copy. In both cases (film displayed on a lightbox or on-screen soft-copy), contrast discrimination is important to ensure that the radiologist detects any relevant information on the radiograph. For this reason, ambient light needs to be kept low, but cannot be completely absent, as enough illumination for paperwork may still be required.

Alter et al. [1982] investigated the influence of ambient light on visual detection of low-contrast targets in a radiograph under a total of 14 lighting conditions. In general, they found that the visual detection rate was higher when the ambient lighting was lower and this was particularly because of extraneous light from surrounding lightboxes. In the same year, Baxter et al. [1982] examined changes in lesion detectability in film radiographs. Their experiments showed that light adaptation effects can influence the detectability of low-contrast patches and that extraneous peripheral light affects visual sensitivity. Subsequent work by Rogers et al. [1987] assessed the effect of reflections on electronically displayed medical images for low levels of ambient light (4–148 lux). They presented two experiments, which showed that changes in stimulus discriminability could be attributed to changes produced in the displayed image by ambient light, rather than by changes in the visual sensitivity of the observer.

Further to the above work, recent years have seen a move to digital radiology in the United States, where it has almost entirely replaced hardcopy film. This has resulted in the establishment of the Digital Imaging and Communications in Medicine (DICOM) standard in 1993, which aims to achieve compatibility between imaging systems. Among its current activities, DICOM provides standards on diagnostic displays, with the goal of visual constancy of images delivered across a network. They have proposed that every sensor quantization level maps to at least one just noticeable difference (JND) on the display device [National Electrical Manufacturers Association 2003]. Their function is derived from Barten's [1992] model of human contrast sensitivity to provide a perceptual linearization of the display device. Annex E of the DICOM grayscale standards describes how the dynamic range of an image may be affected by veiling glare, by noise, or by quantization, in that the theoretically achievable JNDs may not match the realized JNDs that are ultimately perceived. These standards assume that the emissive luminance from the monitor and the ambient light are both measured using a photometer.

Early work on color television characterization acknowledged the influence of surround luminance on observers' preferred gamma settings, finding that the desired tone reproduction curve varied markedly depending on the ambient illumination [Novick 1969; De Marsh 1972]. Ware [2000] has shown the effect of light reflections on the appearance of images. He suggests that a possible solution would be to apply gamma correction with a lower value of gamma than the display device itself would dictate. A value of around $\gamma = 1.5$ is proposed. While the simplicity of this approach is attractive, we believe that a better solution is possible, based on the psychophysical experiments described below.

Recent work on lighting sensitive displays, where the display can sense the illumination of the surrounding environment and render the image content accordingly, has also mentioned the need for adjustment of the image in relation to the ambient light for reasons such as legibility and power consumption [Nayar et al. 2004].

3. MEASURING REFLECTED AMBIENT LIGHT

In order to establish the quantity of light reflected off a computer monitor in commonly encountered viewing environments, and to establish how this influences the perception of contrast, a psychophysical user study was undertaken, with images displayed on cathode ray tube (CRT) monitors. Liquid crystal display (LCD) monitors are growing in popularity, but the image quality is affected by the viewing angle. This is particularly important if the user is outside the optimal viewing position, or if there are multiple users. Studies in radiology to determine the influence of ambient lighting on a CRT and on a LCD screen showed that overall comparison between the two screen types was not statistically significant [Haak et al. 2002] and that monitor type does not have a significant influence on diagnostic accuracy [Cederberg et al. 1999]. Hence, we assume that for applications where perceptual fidelity is of crucial importance, current LCD technology will not be used. However, had there been a way of ensuring a consistent viewing experience for LCDs throughout our experiments, we would have incorporated the use of these screens.

The image that reaches the eye of the observer is a combination of emitted and reflected light. The surface of a CRT screen is typically made of glass and so the reflections on the glass are specular. A full characterization of these reflections would accordingly be viewpoint dependent. For most viewing conditions, direct specular reflections may be minimized with appropriate lighting design [Rea 2000]. We, therefore, worked under the assumption that the environment causes a uniform increase of luminance across the CRT screen. Further, it is assumed that the environment is lit by white light, i.e., color appearance issues are not addressed. (However, the work does not preclude the application of a suitable color appearance model.)

Our user study measured difference thresholds under various levels of illuminance. The difference threshold is the minimum amount by which the intensity of a stimulus must be changed before a JND is detectable [Sekuler and Blake 1994]. We, therefore, use the Weber [1834] fraction as our definition of contrast. Weber's Law is a psychophysical approximation, which states that the ratio between just noticeable luminance change ΔL to mean luminance L is constant, i.e., $\Delta L/L = k$ [Wyszecki and Stiles 2000]. The size of this JND (i.e., ΔL) is a constant proportion of the original stimulus value. Adding a constant term to each pixel reduces our ability to perceive contrast. Weber's Law has been shown to hold in many situations (although the fraction tends to increase at extremely low values) and, thus, can be considered sufficiently robust for our purposes. Plotting detection thresholds against their corresponding background luminances results in a threshold-versus-intensity (TVI) function that is linear over a middle range covering 3.5 log units of background luminance; this middle range corresponds to Weber's Law [Ferwerda 2001].

3.1 Experiment 1: Contrast Discrimination Thresholds

Following the method of Rogers et al. [1987], we predicted that the presence of reflected ambient light in the viewing environment would affect the perceived contrast of an image displayed on a CRT monitor. The research hypothesis was that there exists a significant difference between JND perception in the *dark* condition, JND perception in the *medium* condition, and JND perception in the *light* condition.

3.1.1 *Participants.* Six individuals (three male, three female) participated in this experiment. All had normal or corrected-to-normal vision. All participants were fully adapted to the prevailing illumination conditions before beginning their task. All participants took part in all conditions and the order of their participation was randomized.

3.1.2 *Conditions.* Three light conditions were chosen for this study. In order to act as a reference condition for the experiments, one condition had no ambient light present. The two other conditions were based on common viewing environments observed in the workplace. The first condition (*dark*, 0 lux)—the ground truth—contained no ambient light and consisted of a room painted entirely with matt black paint. The tabletop was draped with black fabric. The only light came from the monitor on which the experimental targets were displayed. The second condition (*medium*, 45 lux) was an office with white walls. No natural light was present. The sole illuminant was an angle-poise desk lamp with a 60-watt incandescent tungsten bulb with tracing paper used to diffuse the light. The third condition (*light*, 506 lux) was the same white-walled office as before, but with overhead fluorescent reflector lights instead of the desk lamp. An example of the set-up used is shown in Figure 2. The ambient illumination

Fig. 2. Example of the experimental set-up.

values for each condition were verified using a Minolta CL-200 180° chromameter. This was mounted on a tripod and placed in a position equivalent to the participants' viewpoints, 70–90 cm from the screen. The CRT was a 19-inch Dell Trinitron monitor placed parallel to the light source to avoid specular reflections. Gamma correction was applied to the displayed images by measuring the output displayed on the screen and comparing it to the input values. This was accomplished by displaying a pattern on screen consisting of horizontal stripes that step through from 0 to 255. Stripes were arranged to equalize the power drain on the screen, so that a pair of adjacent stripes always totaled the maximum voltage of 255. The stripes were also wide enough that they were not affected by flare from adjacent stripes [Travis 1991]. This was carried out for each of the voltage guns to ensure maximum accuracy. The stripes of fixed voltage were measured with a chromameter in a totally dark environment. The resulting values were normalized and a function of the form $y = mx$ was fitted to the natural logarithm of the data to give the value of the best gamma fit. Images were then gamma corrected.

3.1.3 *Stimuli.* The stimuli used in this experiment are noise images with a f^{-2} power spectrum, which are then thresholded. In the Fourier domain, the amplitude spectrum A and phase spectrum P are randomized [Reinhard et al. 2004]:

$$\begin{aligned} A(x, y) &= r_1\, f^{-\alpha/2} \\ P(x, y) &= r_2\, A(x, y) \end{aligned}$$

with r_1 and r_2 uniformly distributed variables, α the desired spectral slope, and $f = \sqrt{x^2 + y^2}$ the frequency. An inverse Fourier transform is then applied to create a grayscale image. This image will

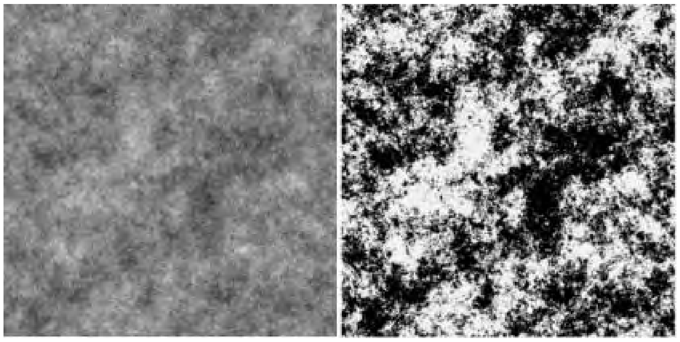


Fig. 3. Pink noise image (*left*) with a spectral slope of -2, and its thresholded counter-part (*right*). We choose a threshold of 128, yielding a spectral slope of -1.68.

have a power spectral slope of -2 if α is chosen to be 2, which closely confirms to the power spectrum of natural image ensembles [Burton and Moorhead 1987; Field 1987].

In addition, images with this particular power spectrum are said to be scale-invariant, which means that the power spectrum of the image as it is formed on the retina does not change with viewing distance. This permits an experiment whereby the distance of the observer does not have to be as rigidly controlled as would be the case with other stimuli.

Observers are not equally sensitive to contrasts at all frequencies, as evidenced by the Campbell–Robson contrast sensitivity curves [Campbell and Robson 1968]. For stimuli other than those with power spectral slopes close to -2, the exact spectral composition of the stimulus would confound the results of the experiments, as well as the usefulness of our approach.

An example of a scale-invariant noise image ($\alpha = 2$, also known as pink noise) is shown on the left in Figure 3. Because of the manner in which this image is created the average grayscale value is 127.5, which is halfway between black and white. We use this value to threshold the image to become two-tone (Figure 3, *right*).

Since thresholding affects the slope of the circularly averaged power spectrum, the thresholded image is no longer strictly scale invariant. We have found that the power spectrum now has a slope of -1.68. To ensure that we are choosing the best possible threshold level, we plot the power spectral slope as function of threshold value in Figure 4. For illustrative purposes, we show the effect of thresholding on the appearance of the images in Figure 5. We observe that the peak of this curve is indeed located around the average luminance value of the image and that, therefore, our choice of threshold is optimal.

Although our thresholded image has a spectral slope, which deviates from -2, we note that a value of -1.68 is still within the range of natural images, which is found to be -1.88 with a standard deviation of ± 0.43 [van der Schaaf 1998].[1] We, therefore, deem these stimuli suitable for our experiments.

During the experiments, we replace the black and white pixels with appropriately chosen gray values to measure just noticeable differences. One of the gray values is kept at a constant level between trials, and we call this background value the "pedestal value." The foreground value differs from the background by varying amounts, i.e., JND.

The experiment was concerned with finding the smallest observable difference between pedestal and foreground under different lighting conditions. Targets had a pedestal value of either 5, 10 or 20% gray,

---

[1] Our power spectral slope estimation procedure is identical to the one employed by van der Schaaf [1998] in his thesis. The image is first windowed with a Kaiser–Bessel window. The Fourier transform is then taken and the power spectrum is computed. After circularly averaging the power spectrum, we fit a straight line through the data using linear regression [Press et al. 1992]

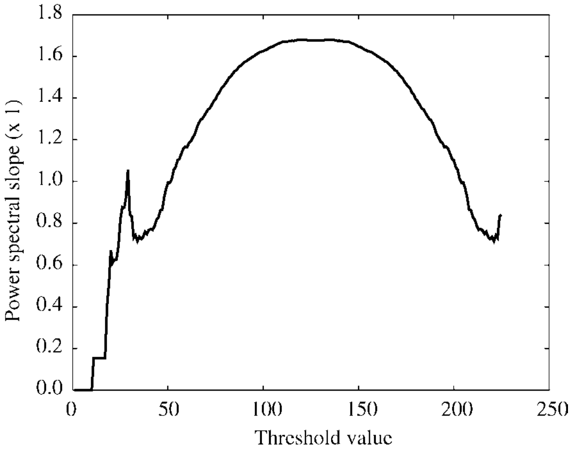


Fig. 4. Power spectral slope as function of luminance threshold value.

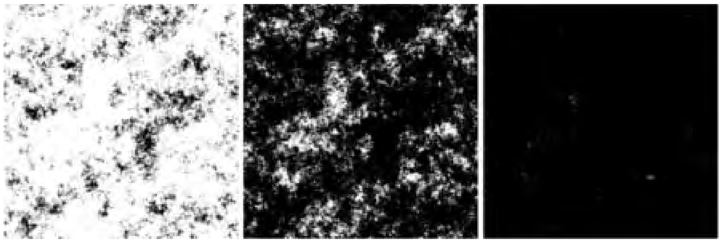


Fig. 5. Pink noise images thresholded with thresholds of 100, 150, and 200.

i.e., as a percentage of the maximum luminance. To maximize the the number of quantization levels, a technique known as *bit-stealing* was employed, whereby 1786 levels of gray can be encoded in a 24-bit color image through a form of dithering that makes use of imperceptible changes in hue [Tyler et al. 1992; Tyler 1997].

3.1.4 *Procedure.* The main experiment was a signal-detection task consisting of 120 trials. A two-alternative forced-choice (2afc) procedures, using two random interleaving staircases, was employed. This took the form of two 0.5 s intervals, separated by 0.5 s of the pedestal gray value, which was followed by 4 s of gray before the beginning of the next trial. The first interval was marked by a beep and the second by a double beep. During one of the intervals, a target was shown. This target filled the monitor screen. The order of presentation of targets was randomized. Participants had to choose whether this target appeared in the first or the second interval. Following five correct selections, the contrast of the target was decreased toward the value of the pedestal gray. Following an incorrect selection, the contrast of the target was set further from the pedestal gray. This resulted in the collection of threshold values for each participant, for each given pedestal value, under each of the ambient light conditions. These values are listed in the Appendix in Tables AI–AIII.

3.1.5 *Results and Discussion.* Because of the small sample size, both means testing and a non-parametric statistical test were deemed appropriate. It was not satisfactory to rely solely on means testing using analysis of variance (ANOVA), as ANOVA generally requires 30+ participants so that a normal distribution of data can be assumed. A nonparametric Friedman test, which does not require an assumption of normal distribution, was, therefore, also conducted.

A repeated-measures ANOVA indicated that overall there was a significant difference in contrast discrimination, depending on the presence of reflected ambient light ($F(2, 10) = 13.21, p = 0.002$). Estimated marginal means showed that the mean JND size increased as the amount of ambient light increased. Specific significant differences were: for a pedestal of 5% gray, $F(2, 10) = 4.636$, $p = 0.038$; for a pedestal of 10% gray, $F(2, 10) = 5.484, p = 0.025$; and for a pedestal of 20% gray, $F(2, 10) = 12.234$, $p = 0.002$.

A Friedman test revealed that when using a pedestal of 5% gray, the difference in JND perception between the three conditions was significant ($\chi^2_{(2)}6.333$, $p = 0.042$), as was the case for a pedestal of 10% gray ($\chi^2_{(2)}9.00$, $p = 0.011$), and 20% gray ($\chi^2_{(2)}10.333$, $p = 0.006$). These results again indicate that ambient lighting has a significant effect on contrast discrimination when carried out on a CRT monitor under the aforementioned conditions.

3.2 Experiment 2: Rapid Characterization

The experiment described above highlights the significance of the contribution of reflected light to the perception of contrast in complex images and provides a JND measurement of contrast perception for the tested level of illumination and display intensity. However, the method is of little use in a practical setting as a result of the lengthy procedure (over $1\frac{1}{2}$ hours per person, excluding periods of rest). Compromise was, therefore, sought between accurate measurement of screen reflections and practical use, with the aim of developing a rapid technique that requires no specialized equipment, using only the user's visual response and display device itself to gather information about the viewing environment. The research hypothesis remained the same as that of experiment 1.

In a manner analogous to simplified determination of the gamma value for a display device [Colombo and Derrington 2001], where the gray patch that most closely matches a series of thin black and white lines on a chart is selected, a simple method for measuring contrast perception involves the display of a stimulus on screen, which is then used to determine the amount of reflected light. The following procedure is almost as straightforward as reading a value off a chart and constitutes a sensible compromise between accuracy and speed. Using a tableau of stimuli under similar conditions to experiment 1, the participants were shown a 10 × 10 grid of squares each containing targets with increasing contrast from the top left to the bottom right of the grid (Figure 6). To make this practical, the targets consisted of random noise images with a power spectral slope of -2, as detailed above.

3.2.1 *Participants.* Twenty-one individuals participated in this experiment. All had normal or corrected-to-normal vision. All participants were fully adapted to the prevailing light conditions before beginning their task. All participants took part in all conditions and the order of their participation was randomized.

3.2.2 *Conditions.* Three light conditions were chosen for this study, similar to those in experiment 1, above: *dark*, 0 lux; *medium*, 80 lux; and *light*, 410 lux. The ambient illumination values were verified as before. Two 17-inch Sun Microsystems CRTs were used, fully calibrated with the appropriate gamma correction applied to the displayed images.

3.2.3 *Procedure.* Again, the experiment constituted a signal-detection task. A tableau of images displayed in a 10 × 10 grid was shown. The pedestal value was set to either 5, 10, or 20% gray. A target of randomly generated $1/f$ noise was displayed in each square of the grid, with the contrast increasing linearly in each square from the top left to the bottom right of the grid. The minimal contrast value (0) increased to a pedestal-dependent maximum contrast value (0.004–0.006, determined through the

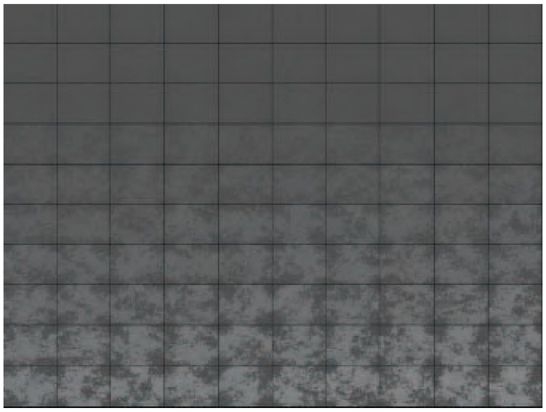


Fig. 6. Grid of squares used for simplified characterization.

results of experiment 1). The participants were given instructions that asked them to click once on the square where they could *just notice* some noise on the gray background. It was explained that "*Just noticeable* means that it is the square closest to appearing blank: the other squares contain either no noise or more noise."

By clicking on their chosen square, another tableau was displayed, this time with the contrast increasing by an exponent of 2, effectively showing more squares closer to the threshold region. With each choice made by the participant, the contrast doubled, until the participant could only see contrast in the high part of the curve, whereupon the power was decreased. For each pedestal value, under each ambient light condition, the participant made five choices, indicating in which part of the tableau they perceived the minimal contrast. These values were then averaged to give an average JND value for each individual, for each pedestal value, under each condition. Again, these values are appended in Tables AIV–AVI.

3.2.4 *Results and Discussion.* A repeated-measures ANOVA revealed an overall significant difference in threshold detection between the three lighting conditions, $F(2, 40) = 58.9, p < 0.001$. These results indicate that when measured by this rapid method, it can be shown that ambient lighting still has a significant effect on contrast discrimination. Specific significant differences were: for a pedestal of 5% gray, $F(2, 40) = 65.770, p < 0.001$; for a pedestal of 10% gray, $F(2, 40) = 37.414, p < 0.001$; and for a pedestal of 20% gray, $F(2, 40) = 35.761, p < 0.001$.

A Friedman test showed that the difference in JND perception between the three conditions for a pedestal of 5% gray was significant ($\chi^2_{(2)}34.048$, $p < 0.001$), as was the case for a pedestal of 10% gray ($\chi^2_{(2)}24.795$, $p < 0.001$), and 20% gray ($\chi^2_{(2)}25.810$, $p < 0.001$). These results correspond to the ANOVA results, confirming the rejection of the null hypothesis.

Although direct comparison cannot be made between the results of experiment 1 and experiment 2, both experiments showed a significant difference between contrast perception under three different levels of reflected ambient light, revealing experiment 2 to be a valid method of measuring changes in contrast perception, yet taking only a fraction of the time of experiment 1 (generally no more than 2 min, in total, per person).

4. CONTRAST ADJUSTMENT

The amount of light reflected by a computer monitor may be indirectly measured with one of the experiments described above. It is envisaged that the viewer establishes a JND (ΔL_d) in darkness and a second JND (ΔL_b) with normal office lights switched on. In both cases, some desired pedestal value L will be used (such as, 20% of the maximum display intensity).

The light that travels from the monitor to the eye is then L in the dark condition and $L + L_R$ in the light condition. The term L_R represents the amount of light diffusely reflected by the monitor and constitutes the unknown value required for adjustment purposes. Using Weber's Law, L_R can be computed with the following equations:

$$\frac{\Delta L_d}{L} = \frac{\Delta L_b}{L + L_R}$$

$$L_R = L\left(\frac{\Delta L_b}{\Delta L_d} - 1\right)$$

Under the assumption that $L_d < L_b$, and, hence, that $L_R > 0$, we should ideally subtract L_R from each pixel to undo the effect of reflected light. The reflections off the monitor would then add on this same amount, thus producing the desired percept. Remapping luminance by subtraction would also yield a function with a derivative of 1 over its range. Any other slope would result in changes in contrast that may affect image perception. However, there are two problems with this approach. First, dark pixels will become negative and are, therefore, impossible to display. Negative pixels could be clamped to zero, but that would reduce the dynamic range, which for typical display devices is already limited. The second problem is that subtraction of L_R leads to underutilization of the available dynamic range at the upper end of the scale.

As previously mentioned, one alternative form of remapping may be to apply gamma correction in an attempt to correct for the additive term L_R [Ware 2000]. By reducing the gamma value applied to the image, the result may become perceptually closer to linear. However, while a value for gamma correction may be chosen such that the pedestal value L is mapped to $L - L_R$, the slope of this function at L will not be 1 and the perceived contrast around the chosen pedestal value will, therefore, still not be the desired ΔL_d. In particular, for a gamma function $f(x) = x^{1/\gamma}$, $\gamma = \log L / \log(L - L_R)$ would then be required to achieve the desired reduction in intensity. The derivative of f would have a slope of $\log_L(L - L_R)(L - L_R)/L$ at L, which will only be 1 if no light is reflected off the screen, i.e., $L_R = 0$. To ensure perceptually accurate display, a function that maps L to $L - L_R$ is necessary, at the very least, while at the same time forcing the derivative at L to 1.

Hyperbolic functions have been proposed to manipulate image contrast [Lu and Healy 1994]:

$$f(x) = \frac{\tanh(ax - b) + \tanh(b)}{\tanh(a - b) + \tanh(b)}$$

The parameters a and b control the slope of the function at 0 and 1. Although this function may be used to adjust contrast, it is not suitable for the control of the slope for some intermediate value, such as pedestal value L.

Histogram equalization is a well-known method for manipulating contrast [Weeks 1996]. Based on the histogram of an image, a function is constructed which remaps the input luminances such that in the output each luminance value is equally likely to occur. Therefore, the remapping function will be different for each image. Although it maximizes contrast, this approach does not allow control over the value and slope of the mapping function at specific control points and is, therefore, not suitable for this application.

Finally, several techniques have been developed, which are spatially variant, i.e., a pixel's luminance is adjusted based on its value as well as the values of neighboring pixels. These methods are prone to contrast reversals, which is generally undesirable. For this reason we do not propose to use spatially variant mechanisms, such as multiscale representations [Lu et al. 1994], genetic algorithms [Munteanu and Lazarescu 1999], and level-set based approaches.

As such, we suggest that none of the commonly used techniques to adjust contrast are suitable to correct for reflections off computer screens and, therefore, develop a novel remapping function in the following section.

4.1 Luminance Remapping

With the ability to measure L_R through the measurement of JNDs, we seek a function that remaps intensities so that the contrast perceived at a single luminance is preserved, i.e., the amount of contrast perceived around the pedestal value L is the initial ΔL_d, thereby adequately correcting for the L_R term. Also, the full dynamic range of the display device should be employed.

It can be observed that subtracting the ambient term L_R from pixels with a luminance value of L will produce the required behavior around L. Furthermore, it is required that the derivative of our remapping function is 1 at L so that contrast ratios are unaffected. For values much smaller and much larger than L, a remapping is desired that is closer to linear to fully exploit the dynamic range of the display device. The function should also be monotonically increasing to avoid contrast reversals. In summary, we are seeking a function $f : [0, m] \to [0, m]$ with the following characteristics:

$$\begin{aligned} f(0) &= 0 \\ f(m) &= m \\ f(L) &= L - L_R \\ f'(L) &= 1 \\ f'(x) &\geq 0 \end{aligned}$$

Although power laws, such as, gamma correction, can not be parameterized to satisfy all the above function requirements, a rational function proposed by Schlick [1994b] may be used as a basis. This function was originally proposed as a tone reproduction operator and a variation was published as a fast replacement for Perlin and Hoffert's [1989] gain function [Schlick 1994a]. The basic function is given by:

$$f(x) = \frac{px}{(p-1)x + 1} \tag{1}$$

where x is an input luminance value in the range $[0, 1]$ and p is a scaling constant in the range $[1, \infty]$.

The list of requirements may be satisfied by splitting the function into two ranges, namely, $[0, L]$ and $[L, m]$. Using Eq. (1), the appropriate substitutions are made for x. As we already know the values for L and L_R, we can solve for the free parameter p. In particular, the input x and the output $f(x)$ is scaled before solving for p.

For the range $[0, L]$, we substitute $x \to x/L$ in Eq. 1 and the output is then scaled by $L - L_R$:

$$\begin{aligned} f_{[0,L]}(x) &= (L - L_R)\frac{p\frac{x}{L}}{(p-1)\frac{x}{L} + 1} \\ &= \frac{(L - L_R)px}{x(p-1) + L} \end{aligned}$$

This satisfies the requirements that $f_{[0,L]}(0) = 0$ and $f_{[0,L]}(L) = L - L_R$. To satisfy the constraint that the slope of $f_{[0,L]}$ is 1 at L, the following equation can be solved for p:

$$\begin{aligned} f'_{[0,L]}(x) &= \frac{p(L - L_R)}{L((p-1)x/L + 1)} - \frac{(p-1)px(L - L_R)}{L^2((p-1)x/L+1)^2} \\ &= \frac{p(L - L_R)L}{(xp - x + L)^2} \\ &= 1 \end{aligned}$$

By substituting $x = L$, then

$$p = \frac{(L - L_R)}{L}$$

For the range $[L, m]$, we substitute $x \to (x - L)/(m - L)$ in Eq. (1), scale the output by $m - L + L_R$, and add $L - L_R$ to the result:

$$f_{[L,m]}(x) = \frac{p\dfrac{x-L}{m-L}(m - L + L_R)}{(p-1)\dfrac{x-L}{m-L} + 1} + L - L_R$$

The above satisfies the requirements that $f_{[L,m]}(L) = L - L_R$ and $f_{[L,m]}(m) = m$. The derivative of this function is:

$$f'_{[L,m]}(x) = \frac{p(m - L + L_R)}{(m-L)\left(\dfrac{(p-1)(x-L)}{m-L} + 1\right)} - \frac{(p-1)p(x-L)(m-L+L_R)}{(m-L)^2\left(\dfrac{(p-1)(x-L)}{m-L} + 1\right)^2}$$

Again, p is solved by requiring $f'_{[L,m]}(L)$ to be 1, resulting in

$$p = \frac{(m - L)}{(m - L + L_R)}$$

By making the appropriate substitutions of p and simplifying the equation, the function that remaps luminance to correct for the loss of contrast because of screen reflections L_R is given by:

$$f(x) = \begin{cases} \dfrac{(L - L_R)^2 x}{L^2 - L_R x} & \text{if } 0 \le x \le L \\[2ex] \dfrac{x - L}{1 - \dfrac{L_R(x-L)}{(m - L + L_R)(m - L)}} + L - L_R & \text{if } L \le x \le m \end{cases}$$

For a pedestal value L of approximately one-third, the maximum value $m = 255$, a set of curves is plotted in Figure 7. The different curves were created by varying the amount of light L_R reflected off the monitor.

Figure 8 shows the success of the remapping function applied to images under different ambient light values (L_R). Given the limited dynamic range of most current display devices, it is not possible to adjust the contrast for all bright, dark, and intermediate areas of an image. However, the above remapping function provides a sensible trade-off between loss of detail in the brightest and darkest

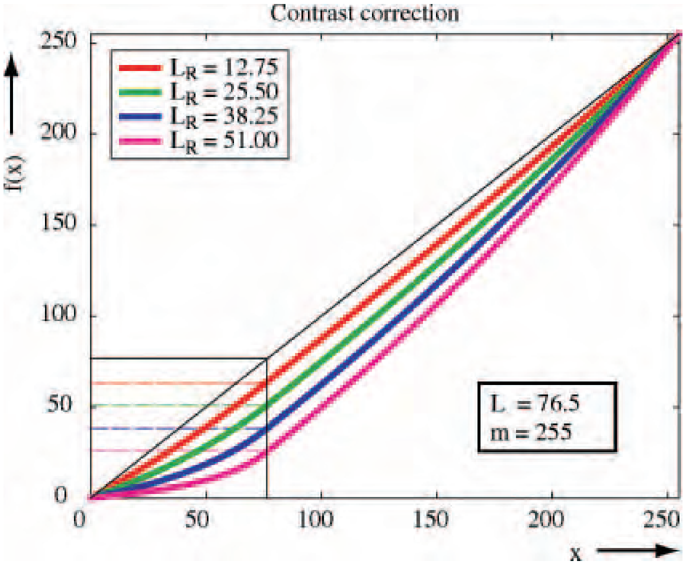
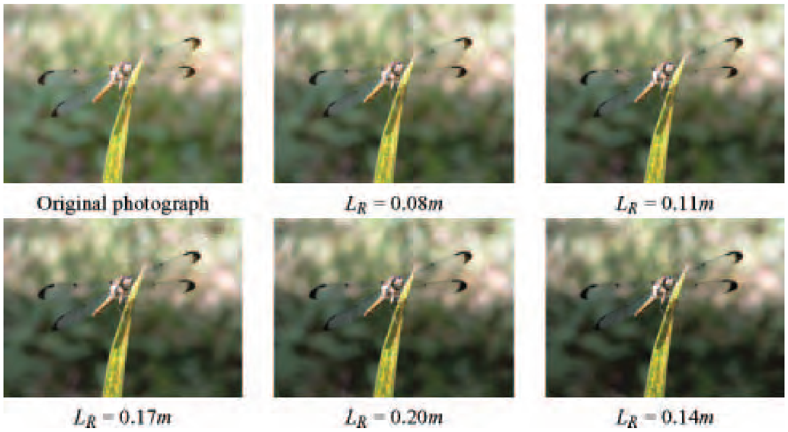


Fig. 7. Remapping functions for L_R set to 5, 10, 15, and 20% of the maximum display value m. The pedestal value was set to $L = 0.3\,m$ for demonstration purposes. In practice, a base luminance value of $L = 0.2\,m$ is appropriate.



Original photograph $L_R = 0.08m$ $L_R = 0.11m$

$L_R = 0.17m$ $L_R = 0.20m$ $L_R = 0.14m$

Fig. 8. Uncorrected photograph followed by a progression of corrected images. In each case, L is set to $= 0.2m$ and $m = 255$.

areas of the image, while at the same time allowing the flexibility to choose which pedestal value of L the remapping produces accurate contrast perception. While a value of $L = 0.2m$ will be appropriate for many practical applications, the function is easily adjusted for different values of L. Only the two JNDs need to be re-measured, after which L_R may be computed and inserted into the above equation. A further advantage of this function over other contrast adjustment methods is that the data does not need to be scaled between 0 and 1, since the maximum value m is given as a parameter.

A comparison with the aforementioned existing remapping methods of a reduced gamma value and histogram equalization is given in Figure 9. The top two images show the original photograph as it

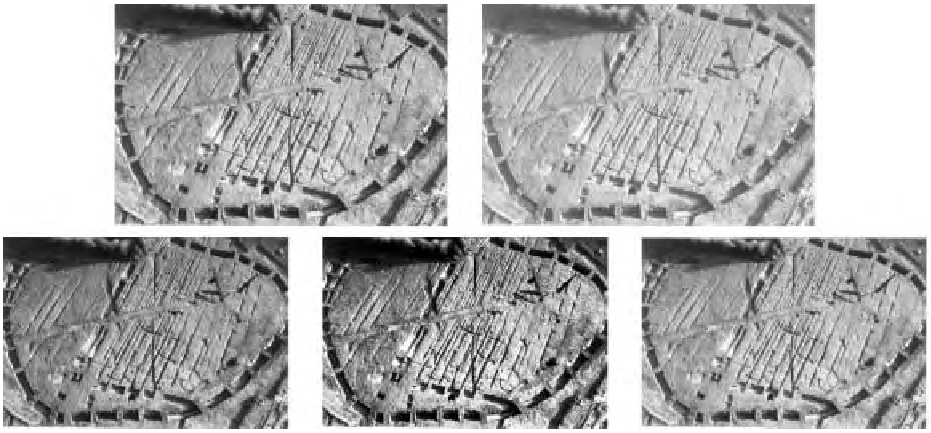


Fig. 9. Comparison with other techniques. *Top*: original image (*left*) and original uncorrected image under ambient illumination, L_R = $0.13m$ (right). *Bottom*: correction using a reduced gamma value (*left*), using histogram equalization (center), and using our algorithm, $L = 0.2$ (*right*). (Photograph courtesy of F. Walsh, ©2003.)

appears when viewed in darkness (*left*) and when viewed in the presence of ambient illumination (*right*). The value L_R is $0.13m$. The reduction in perceived contrast because of the ambient term is notable, with shadow information and fine detail being lost because of reflected ambient light. The bottom left and center images are the result of applying existing remapping techniques to the uncorrected image. The image on the bottom left has been corrected using a reduced gamma value. This has darkened the image as a whole—an undesirable effect. The bottom center image has been corrected using histogram equalization. This has led to considerable darkening in some areas and undesirable lightening in others. It does not preserve the contrast appearance of the original image. The bottom right image has been corrected using our luminance remapping algorithm, using a value of $L = 0.2m$. The contrast ratios have been preserved and the overall appearance is closest to that of the original.

4.2 Function Inversion

Our forward algorithm presented above is suitable to display images that were created for viewing in optimal conditions. However, in many practical cases images are created using specific displays located in uncalibrated viewing environments. Assuming that such images are optimal for the viewing environment in which they were created, it may be useful to convert them for display in a different viewing environment. An effective way to accomplish this is by transforming the image into a standard space that is independent of the viewing environment. This is analogous to the profile connection space used in ICC profiles [ICC (International Color Consortium) 2003]. ICC profiles are normally used to convert images for reproduction on different display devices, such that the perception of the displayed material is least affected. It can be envisaged that the methodology and algorithm described in this paper could become part of the ICC file format, since it would address device dependent issues not covered by ICC profiles to date.

The first step in converting between the viewing environment that was used to create an image (the *source environment*) and some other display environment would be to undo the effect of the source environment. Hence, it is desirable to convert such images to a hypothetical viewing environment in which the screen does not reflect light. This may be achieved by measuring ΔL_d and ΔL_b for the source environment, computing L_R, and then applying the inverse transformation to the image:

$$f_{\text{inv}}(x) = \begin{cases} \dfrac{xL^2}{(L - L_R)^2 + xL_R} & 0 \leq x \leq L - L_R \\[2ex] \dfrac{x(m - L)^2 + mL_R(x + m + L_r - 2L)}{(m - L)^2 + L_R(x + m + L_r - 2L)} & L - L_R \leq x \leq m \end{cases}$$

For the destination environment $f(x)$ may then be applied prior to display. One limitation of this approach is that for both forward and inverse transformations, the same pedestal value L needs to be used. However, it would not be unreasonable to standardize by fixing L to $0.2\,m$ such that middle gray is always displayed correctly.

4.3 Color Space

Most images are given in a device-dependent color space. While it is possible to apply the remapping function to the individual color channels, this is not recommended. Nonlinear scaling functions, such as the one described above, will alter the color ratios for individual pixels, leading to changes in chromatic appearance. This would be an undesirable side effect of the algorithm, which is easily avoided by applying the equation to the luminance channel only. It is, therefore, necessary to convert to a different color space, which has a separate luminance channel, such as XYZ or Lab. These conversions require knowledge of the image's white point, which more often than not is unknown. If the white point is known, an appropriate conversion matrix may be constructed [Poynton 2003]. In many cases, it may be reasonable to make the gray-world assumption, i.e., the average reflective color of a scene is gray. If the average pixel value of the image deviates from gray, this may be attributed to the illuminant. Under the gray-world assumption, the average pixel value is a good estimate of the scene's white-point. Otherwise, one can resort to white-point estimation techniques [Cardei et al. 1999] or simply estimate that the white point is always D65. This will be true to a first approximation for outdoor photographs.

5. VALIDATION OF LUMINANCE REMAPPING

The validation of the algorithm follows the form of experiment 2—the rapid measurement procedure described above. Whereas experiment 2 measured JND discrimination under three different lighting conditions, the validation experiment required JND measurement under two conditions: light and dark. This could then establish the effect of the light condition on contrast perception. A third iteration of the validation experiment could then be carried out under the same light conditions, but with our luminance remapping algorithm applied to the stimuli.

The research hypotheses were as follows: that JND perception in the *dark* condition is significantly better than JND perception in the *light* condition and that JND perception for the corrected stimuli shown in the *light* condition is significantly better than JND detection of uncorrected stimuli, shown in the *light* condition.

Seventeen individuals participated in this experiment. All had normal or corrected-to-normal vision. All participants were fully adapted to the prevailing light conditions before beginning their task. All participants took part in all conditions and the order of their participation was randomized. Three pedestal values of gray were used: 10, 20, and 35%. The resulting average JND values for each participant can be seen in Tables AVII-AIX in the Appendix.

A dependent means t-test indicated a significant difference between JND values measured in the *dark* condition and uncorrected stimulus JND values measured in the *light* condition: $t(16) = 2.95$, $p < 0.005$ for a pedestal of 10% gray, $t(16) = 3.01$, $p < 0.005$ for 20% gray, and $t(16) = 3.99$, $p < 0.0006$ for 35% gray. In addition, there was a significant difference between JND values measured using corrected and uncorrected stimuli in the *light* condition: $t(16) = 2.73$, $p < 0.008$ for a pedestal of 10% gray, $t(16) = 3.01$, $p < 0.005$ for 20% gray, and $t(16) = 1.94$, $p < 0.035$ for 35% gray. In addition, as might be anticipated, no significant difference was found between JND values measured in the *dark* condition and JND values measured using the corrected stimulus in the *light* condition. However, as mentioned above, this represents a null hypothesis and, therefore, cannot be directly tested, nor (technically) be accepted [Aberson 2002].

A Wilcoxon Signed Ranks test (the nonparametric equivalent of a paired t-test) revealed that JND values were significantly higher in the *light (uncorrected)* condition than in the *dark* condition: $z = 2.6$, $p < 0.005$ for a pedestal of 10% gray, $z = 2.62$, $p < 0.005$ for 20% gray, and $z = -3.37$, $p < 0.0005$ for a pedestal of 35% gray. As predicted, the JND values were also significantly higher in the *light (uncorrected)* condition than in the *light (corrected)* condition, $z = 2.28$, $p < 0.02$ for a pedestal of 10% gray, $z = 2.24$, $p < 0.002$ for 20% gray, and $z = 2.24$, $p < 0.002$ for 35% gray. These values support those of the above t-test.

The results indicate that when applied to an image that is perceived differently under increased illumination, our algorithm can restore the original contrast appearance, resulting in an image that does not significantly differ from the way it was intended.

6. CONCLUSIONS AND FUTURE WORK

Through validation studies we have confirmed that light reflected off a monitor significantly alters contrast perception. We have devised a simple technique to estimate by how much the appearance of contrast is altered. By specifying a simple task that every viewer can carry out in a short amount of time, we avoid using expensive equipment, such as, photometers or spectroradiometers. A straightforward rational function is then used to adjust the contrast of images based on the measurements made by each viewer. This produces correct perception of contrast for one luminance value, and approximately correct perception of contrast for all other values.

We realize that for some specific applications, there is no substitute for extensive and methodical calibration of equipment and provision of a specialized viewing environment. This includes areas such as fabric dyeing, or prepress advertising, where perceptual fidelity is imperative and the means to obtain this are achievable. However, despite this, we feel that there is still an audience for our work. Gamma correction, in its short-cut form, is widely used by digital photographers, especially by amateur photographers who do not have the specialized equipment needed to calibrate their monitors. In the same way that gamma correction via a chart is an estimate, and not a full system calibration, we have presented a short-cut method that is similarly an estimate, and not a full calibration. Our work can be seen as an intermediate step between a complete lack of calibration and fully compliant specification. There is a necessary trade-off between accuracy and cost. Therefore, our work, like short-cut gamma correction, is a usable approach for people concerned about the effect of ambient lighting, yet unable to meet rigid specifications.

Thus far, our work has been confined to the measurement of contrast detection, but we would like to extend this work in the future to cover the perception of complex images, where contrast is variable and above threshold level [Peli 1990]. This would require extensive psychophysical validation that is beyond the scope of this paper.

For applications such as medical and scientific visualization, photography, and others, our procedure and algorithm provides a significantly simplified alternative to gain control over the perception of displayed material. It fits alongside existing correction steps, such as, gamma correction and color appearance models and addresses and solves a significant problem in image display. The visual self-calibration procedure lends itself well to use on the Internet where perceptual consistency may be desirable among online images that are viewed worldwide on a variety of display devices. Finally, this approach may see use in ICC color profiles where it not only allows images to be exchanged between different devices, but between devices located in specific viewing environments.

APPENDIX

Table AI. Experiment 1: Average JND Results for Each Participant, for Each Condition (Pedestal Value = 5% Gray)

Participant	Dark, Pedestal 5% Gray	Medium, Pedestal 5% Gray	Light, Pedestal 5% Gray
A	0.005534	0.005307	0.006338
B	0.004980	0.005167	0.006771
C	0.005460	0.005530	0.005955
F	0.004962	0.005472	0.005759
G	0.005964	0.005688	0.009213
H	0.006305	0.005699	0.005855

Table AII. Experiment 1: Average JND Results for Each Participant, for Each Condition (Pedestal Value = 10% Gray)

Participant	Dark, Pedestal 10% Gray	Medium, Pedestal 10% Gray	Light, Pedestal 10% Gray
A	0.009335	0.009250	0.009415
B	0.008307	0.007464	0.010490
C	0.008153	0.008384	0.008597
D	0.009786	0.008213	0.010583
E	0.007852	0.009602	0.012601
F	0.006976	0.008490	0.009529

Table AIII. Experiment 1: Average JND Results for Each Participant, for Each Condition (Pedestal Value = 20% Gray).

Participant	Dark, Pedestal 20% Gray	Medium, Pedestal 20% Gray	Light, Pedestal 20% Gray
A	0.007740	0.009428	0.008280
B	0.007586	0.007854	0.008774
C	0.007002	0.007874	0.010476
D	0.006343	0.009005	0.009404
E	0.007272	0.009241	0.010531
F	0.008031	0.008764	0.010011

Table AIV. Experiment 2: Average JND Results for Each Participant, for Each Condition (Pedestal Value = 5% Gray)

Participant	Dark, Pedestal 5% Gray	Medium, Pedestal 5% Gray	Light, Pedestal 5% Gray
A	0.001147	0.002329	0.005741
B	0.00294	0.003125	0.00552
C	0.002296	0.001081	0.002214
D	0.001163	0.001837	0.003882
E	0.000997	0.001691	0.003519
F	0.00294	0.003064	0.005103
G	0.001212	0.0021	0.005535
H	0.002192	0.00294	0.003077
I	0.00294	0.003036	0.004488
J	0.001584	0.003603	0.003603
K	0.0021	0.002429	0.00316
L	0.000913	0.000936	0.003155
M	0.00161	0.00294	0.004824
N	0.002814	0.003031	0.004622
O	0.002856	0.002854	0.003302
P	0.001876	0.00294	0.004205
Q	0.002338	0.00296	0.004461
R	0.001079	0.001416	0.002958
S	0.000937	0.001166	0.002591
T	0.001293	0.001583	0.003607
U	0.00149	0.002315	0.004438

Table AV. Experiment 2: Average JND Results for Each Participant, for Each Condition (Pedestal Value = 10% Gray)

Participant	Dark, Pedestal 10% Gray	Medium, Pedestal 10% Gray	Light, Pedestal 10% Gray
A	0.001934	0.001828	0.003507
B	0.004145	0.00447	0.006847
C	0.003061	0.001392	0.003267
D	0.00229	0.001933	0.003468
E	0.000974	0.002255	0.003238
F	0.003741	0.003625	0.007257
G	0.001233	0.002507	0.004464
H	0.003741	0.003804	0.0039
I	0.003742	0.003294	0.005527
J	0.002887	0.00507	0.00507
K	0.003423	0.003181	0.002432
L	0.001287	0.00114	0.002318
M	0.002825	0.003741	0.005918
N	0.003633	0.003681	0.006583
O	0.005241	0.004153	0.005529
P	0.001735	0.002776	0.004713
Q	0.002935	0.003397	0.005928
R	0.001053	0.002022	0.002299
S	0.001373	0.00091	0.002747
T	0.001899	0.001461	0.003741
U	0.002896	0.003187	0.006389

Table AVI. Experiment 2: Average JND Results for Each Participant, for Each Condition (Pedestal Value = 20% Gray)

Participant	Dark, Pedestal 10% Gray	Medium, Pedestal 10% Gray	Light, Pedestal 10% Gray
A	0.003177	0.002361	0.004056
B	0.005488	0.007103	0.008508
C	0.005101	0.002269	0.003732
D	0.003603	0.003345	0.005417
E	0.00151	0.003154	0.004442
F	0.00703	0.005741	0.009323
G	0.003024	0.004154	0.007079
H	0.004991	0.004988	0.00589
I	0.006382	0.0053	0.008128
J	0.005653	0.005129	0.005751
K	0.00494	0.005506	0.005453
L	0.000784	0.001867	0.002306
M	0.004789	0.00515	0.008508
N	0.005095	0.006597	0.008573
O	0.008266	0.006645	0.00893
P	0.00344	0.004784	0.006922
Q	0.005094	0.004935	0.007406
R	0.000906	0.001835	0.003352
S	0.001226	0.001634	0.002478
T	0.002498	0.002432	0.004788
U	0.004589	0.004202	0.008095

Table AVII. Validation Experiemnt: Average JND Values for Stimuli Detection in Dark, Light, and Light-Corrected Conditions for Each Participant (Pedestal Value of 10% Gray)

	Dark	Light	Correct
A	0.002058	0.0031422	0.00215
B	0.0022424	0.0031404	0.0025848
C	0.0032728	0.0032728	0.003938
D	0.0129324	0.0108904	0.0109648
E	0.001579	0.0021354	0.002232
F	0.001179	0.002585	0.0022226
G	0.0005668	0.002167	0.0026248
H	0.0032728	0.0033286	0.0026102
I	0.0027938	0.002855	0.0028212
J	0.0028622	0.0031844	0.002642
K	0.0015112	0.0023388	0.002149
L	0.0018216	0.002583	0.0018612
M	0.003224	0.0042718	0.0040008
N	0.0032286	0.0032286	0.0033544
O	0.0032728	0.0055368	0.0043186
P	0.0033286	0.0044918	0.0032728
Q	0.0032728	0.0049588	0.0033192

Table AVIII. JND Values for Stimuli Detection in Dark, Light, and Light-Corrected Conditions for Each Participant (Pedestal Value of 20% Gray)

	Dark	Light	Correct
A	0.0054082	0.0057112	0.0048982
B	0.0051134	0.0070888	0.0066044
C	0.0060704	0.0061332	0.0057958
D	0.0151746	0.0131466	0.017401
E	0.0027418	0.0046218	0.0025942
F	0.004101	0.0058332	0.0026678
G	0.0035246	0.0053028	0.002925
H	0.0062584	0.0064264	0.0049734
I	0.0057878	0.0056702	0.0052112
J	0.0048316	0.0064494	0.0072166
K	0.0049352	0.0049772	0.0038302
L	0.0045968	0.0057324	0.0037092
M	0.0060098	0.007504	0.0061566
N	0.0060704	0.0061808	0.0059654
O	0.0068122	0.0089828	0.007843
P	0.0055238	0.0068134	0.0041874
Q	0.0076578	0.007696	0.008573

Table AIX. JND Values for Stimuli Detection in Dark, Light, and Light-Corrected Conditions for Each Participant (Pedestal Value of 35% Gray)

	Dark	Light	Correct
A	0.0062912	0.0071574	0.0055206
B	0.0075026	0.0091054	0.0088026
C	0.007749	0.0117096	0.0092682
D	0.0182654	0.0252948	0.0192198
E	0.0025296	0.0028958	0.0027232
F	0.0018656	0.006713	0.0037794
G	0.0052678	0.0071286	0.0030218
H	0.0092814	0.011511	0.0106592
I	0.006927	0.0139418	0.0074978
J	0.007206	0.0088334	0.0061198
K	0.0056928	0.0069172	0.0086292
L	0.0057496	0.0070088	0.006795
M	0.0120892	0.0111422	0.010133
N	0.0072994	0.009717	0.0113816
O	0.0112014	0.0117872	0.0112664
P	0.007143	0.0081946	0.00724
Q	0.0113616	0.011605	0.0130164

REFERENCES

Aberson, C. 2002. Interpreting null results. *Journal of Articles in Support of the Null Hypothesis 1,* 3, 36–42.

Alter, A., Kargas, G., Kargas, S., Cameron, J., and McDermott, J. 1982. The influence of ambient and viewbox light upon visual detection of low-contrast targets in a radiograph. *Investigative Radiology 17*, 402–406.

Ashdown, I. and Franck, P. 1995. Luninance fradients: Photometric analysis and perceptual reproduction. In *IESNA Annual Conference Technical Papers.* Illuminating Engineering Society of North America.

Barten, P. 1992. Physical model for the contrast sensitivity of the human eye. In *Proceedings of SPIE 1666*. 57–72.

Bartleson, C. and Breneman, E. 1967. Brightness perception in complex fields. *Journal of the Optical Society of America 57,* 7.

Baxter, B., Ravindra, H., and Normann, R. 1982. Changes in lesion detectability caused by light adaptation in retinal photoreceptors. *Investigative Radiology 17*, 394–401.

Besuijen, K. and Spenkelink, G. 1998. Standardizing visual display quality. *Displays 19*, 67–76.

Burton, G. and Moorhead, I. 1987. Color and spatial structure in natural scenes. *Applied Optics 26,* 1 (Jan.), 157–170.

Campbell, F. and Robson, J. 1968. Application of Fourier analysis to the visibility of gratings. *Journal of Physiology 197*, 551–566.

Cardei, V., Funt, B., and Barnard, K. 1999. White point estimation for uncalibrated images (color constancy). In *Proceedings of the IS&T/SID Seventh Color Imaging Conference: Color Science, Systems and Applications*. 97–100.

Cederberg, R., Frederiksen, N., Benson, B., and Shulman, J. 1999. Influence of the digital image display monitor on observer performance. *Dentomaxillofacial Radiology 28*, 203–207.

Colombo, E. and Derrington, A. 2001. Visual calibration of CRT monitors. *Displays 22*, 87–95.

De Marsh, L. 1972. Optimum telecine transfer characteristics. *Journal of the Society of Motion Picture and Television Engineers 81.*

Devlin, K., Chalmers, A., and Purgathofer, A. W. 2002. STAR: Tone reproduction and physically based spectral rendering. In *State of the Art Reports, Eurographics 2002*. 101–123.

DiCarlo, J. and Wandell, B. 2000. Rendering high dynamic range images. In *Proceedings of the SPIE Electronic Imaging 2000 conference*. vol. 3965. 392–401.

Evans, R. 1959. *Eye, Film and Camera in Color Photography*. Wiley, New York.

Fairchild, M. 1995. Considering the surround in device independent color imaging. *Color Research and Application 20*, 352–363.

Fairchild, M. 2005. *Color Appearance Models*, 2nd Ed. Wiley, New York.

Federal Aviation Administration 2000. *DOT/FAA/CT-96/1 HUMAN FACTORS DESIGN GUIDE FAA Technical Center For Acquisition*. Federal Aviation Administration.

Ferwerda, J. 2001. Elements of early vision for computer graphics. *IEEE Computer Graphics and Applications 21,* 5, 22–33.

Field, D. 1987. Relations between the statistics of natural images and the response properties of cortical cells. *Journal of the Optical Society of America A 4,* 12 (Dec.), 2379–2394.

Haak, R., Wicht, M., Hellmich, M., Nowak, G., and Noack, M. 2002. Influence of room lighting on grey-scale perception with a CRT and TFT monitor display. *Dentomaxillofacial Radiology 31*, 193–197.

Hunt, R. 2004. *The Reproduction of Colour*, 6th ed. Wiley, New York.

ICC (International Color Consortium) 2003. *Specification ICC.1:2003-09, File Format for Color Profiles, Version 4.1.0*. ICC (International Color Consortium).

ISO (International Standards Organisation) 2000. *ISO3664 Viewing conditions—Graphic technology and photography*, 2nd Ed. ISO (International Standards Organisation).

Lu, J. and Healy, D. 1994. Contrast enhancement via multiscale gradient transformation. In *Proceedings of the 16th IEEE International Conference on Image Processing*. vol. II. 482–486.

Lu, J., Healy, D., and Weaver, J. 1994. Contrast enhancement of medical images using multiscale edge representations. *Optical Engineering 33,* 7, 2151–2161.

Moroney, N., Fairchild, M., Hunt, R., Li, C., Luo, M., and Newman, T. 2002. The CIECAM02 color appearance model. In *IS&T 10th Color Imaging Conference*. Scottsdale, 23–27.

Munteanu, C. and Lazarescu, V. 1999. Evolutionary contrast stretching and detail enhancement of satellite images. In *Proceedings of MENDEL'99*. 94–99.

National Electrical Manufacturers Association. 2003. *Digital Imaging and Communications in Medicine (DICOM) Part 14: Grayscale Standard Display Function*. National Electrical Manufacturers Association.

Nayar, S., Belhumeur, P., and Boult, T. 2004. Lighting sensitive displays. *ACM Transactions on Graphics 23,* 4 (Oct.), 963–979.

Novick, S. 1969. Tone reproduction from color telecine systems. *Bristish Kinematography Sound and Television*.

OBORNE, D. 1995. *Ergonomics at Work*, 3rd Ed. Wiley, New York.

PELI, E. 1990. Contrast in complex images. *Journal of the Optical Society of America A 7,* 10, 2032–2040.

PERLIN, K. AND HOFFERT, E. M. 1989. Hypertexture. In *Proceedings of the 16th Annual Conference on Computer Graphics and Interactive Techniques*. ACM Press, New York. 253–262.

POYNTON, C. 1998. The rehabilitation of gamma. In *Human Vision and Electronic Imaging III*. *Proceedings of SPIE/IS&T Conference*.

POYNTON, C. 2003. *Digital Video and HDTV: Algorithms and Interfaces*. Morgan Kaufmann Publishers, San Francisco, CA.

PRESS, W. H., FLANNERY, B. P., TEUKOLSKY, S. A., AND VETTERLING, W. T. 1992. *Numerical Recipes in C: The Art of Scientific Computing*, 2nd Ed. Cambridge University Press, Cambridge.

REA, M., Ed. 2000. *IESNA Lighting Handbook*, 9th Ed. Illuminating Engineering Society of North America.

REILLY, J. AND FREY, F. 1996. Recommendations for the evaluation of digital images produced from photographic, microphotographic, and various paper formats. Report to the Library of Congress.

REINHARD, E., SHIRLEY, P., ASHIKHMIN, M., AND TROSCIANKO, T. 2004. Second order image statistics in computer graphics. In *1st ACM Symposium on Applied Perception in Graphics and Visualization*.

REINHARD, E., WARD, G., PATTANAIK, S., AND DEBEVEC, P. 2005. *High Dynamic Range Imaging*. Morgan Kaufmann, San Francisco, CA.

ROGERS, D., JOHNSTON, R., AND PIZER, S. 1987. Effect of ambient light on electronically displayed medical images as measured by luminance-discrimination thresholds. *Journal of the Optical Society of America A 4,* 5, 976–983.

SCHLICK, C. 1994a. Fast alternatives to Perlin's bias and gain functions. In *Graphics Gems IV*. Academic Press, New York 401–403.

SCHLICK, C. 1994b. Quantization techniques for visualization of high dynamic range pictures. In *5th Eurographics Workshop on Rendering.* Eurographics.

SEKULER, R. AND BLAKE, R. 1994. *Perception*, 3rd Ed. McGraw-Hill, New York.

STEVENS, J. AND STEVENS, S. 1963. Brightness function: effects of adaptation. *Journal of the Optical Society of America 53*, 375–385.

TILLER, D. AND VEITCH, J. 1995. Perceived room brightness: pilot study on the effect of luminance distribution. *Lighting Research and Technology 27,* 2, 93–103.

TRAVIS, D. 1991. *Effective Color Displays*. Academic Press, New York.

TUMBLIN, J. AND RUSHMEIER, H. 1993. Tone reproduction for realistic images. *IEEE Computer Graphics & Applications 13,* 6 (Nov.), 42–48.

TYLER, C. 1997. Colour bit-stealing to enhance the luminance resolution of digital displays on a single-pixel basis. *Spatial Vision 10,* 4, 369–377.

TYLER, C., CHAN, H., LIU, L., MCBRIDE, B., AND KONTSEVICH, L. 1992. Bit-stealing: How to get 1786 or more grey levels from an 8-bit color monitor. In *SPIE Proceedings (Human Vision, Visual Processing & Digital Display III)*. vol. 1666.

VAN DER SCHAAF, A. 1998. Natural image statistics and visual processing. Ph.D. thesis, Rijksuniversiteit Groningen, The Netherlands.

WANDELL, B. 1995. *Foundations of Vision*. Sinauer Associates, Sunderland, MA.

WARD LARSON, G., RUSHMEIER, H., AND PIATKO, C. 1997. A visibility matching tone reproduction operator for high dynamic range scenes. *IEEE Transactions on Visualization and Computer Graphics 3,* 4 (Oct.–Dec.), 291–306.

WARE, C. 2000. *Information Visualization: Perception for Design*. Morgan Kauffman, San Francisco, CA.

WATT, A. 2000. *3D Computer Graphics*, 3rd Ed. Addison-Wesley, New York.

WEBER, E. 1834. *Annotationes Anatomicae et Physiologicae*. Kohler, Leipzig, Chapter De Pulsu, Resorptione, Auditu. et Tactu.

WEEKS, A. 1996. *Fundamentals of Electronic Image Processing*. SPIE/IEEE Press.

WYSZECKI, G. AND STILES, W. 2000. *Color Science*, 2nd Ed. Wiley, New York, NY.

Received April 2004; revised November 2005; accepted January 2006