A Study of the Relative Tonal Transfer to Soft Copy Output Devices

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Abstract: The calibration and accurate modeling of high resolution color monitors is fundamental to the role they play as editorial stations in Color Electronic Prepress Systems (CEPS). However, the work does not end with a colorimetric characterization of the output device. An important part of "soft proofing" involves understanding the contribution of relative tone reproduction to similarity of appearance on media of different dynamic range and maximum luminance. Bartleson and Breneman drew attention to this factor in a study in which people were asked to assign subjective magnitudes to discrete regions of scene luminance in conventional images. In this paper we re-examine their equation for rendering constant relative brightness, applied to the situation of soft- to hardcopy-proof agreement. We describe an experiment using images which have no "meaning" or perceptual associations but which have the same overall spatial statistics as conventional images. We review methods for generating phase-randomized, monochrome images from conventional images having various luminance probability distributions (e.g., "low- or "high-key" pictures.) Halftone proofs of such images were made for comparison to renditions on the monitor which use Bartleson and Breneman's formula for tonal remapping and one based on uniform gradients of L* (CIE Psychometric Lightness). Subjective preferences for one remapping over the other were determined by "forced choice" comparisons between the two monitor renditions and the proof. Implications of the results and the potential of the technique are discussed.

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Introduction

Modern electronic prepress systems allow a user to evaluate an image as a soft copy proof on a CRT monitor before the final hard copy proof is made. In order that soft-proofing represent the final product, there must be monitor to proof agreement of all aspects of the image. In this study, we will concern ourselves only with the question of tone reproduction. The physical characteristics of monitor and proof are such that the luminances at corresponding image points differ. Thus exact tone reproduction is not possible. The perception of accurate tone reproduction however *is* possible, and is thought to depend upon achieving equal relative brightness between all corresponding points of the two reproductions. This implies that a transformation of monitor luminances is necessary for agreement with the hard-copy proof. The concern of this paper is the establishment of a technique for the evaluation of luminance mappings.

Previous Work

Bartleson and Breneman (1967) studied the problem of constancy of relative brightness using photographic materials. They used a psychological procedure called magnitude estimation (Stevens, 1961) which requires subjects to assign quantities (relative to highlight) to particular elements of a scene. Transparencies were projected at various levels of illuminance onto a dark background and photographic prints were viewed under various levels of illumination with a white surround. Their results suggested that perceived relative brightness in complex scenes depends upon both the highlight luminance in the scene and the state of adaptation as influenced by the surround. These factors were thought to contribute an "exponential decay" to the power law dependency of brightness (perceived magnitude) on luminance originally documented by Stevens (1961).

Bartleson and Breneman's formulation implies that it is possible to identify scene elements on a transparency which had the same relative brightness as elements on a print. Were this true, it should be possible to remap luminances of individual scene elements in such a way as to achieve overall correspondence between the media. They were unable to test this directly because conventional exposure and development techniques did not permit manipulation of luminances of individual scene elements. With the advent of modern digital image recorders (for film and CRT's), the addressing of individual pixels is possible. In particular, it is possible to test their formulation on the monitor/proof tone reproduction problem.

Intent Of This Study

We have two criticisms of the Bartleson-Breneman approach.
1.) Magnitude estimation is a difficult psychophysical task, especially where luminances are to be judged in complex scenes. This may explain why almost half of their subjects had to be eliminated due to inconsistent results.
2.) The judgement of brightness of localized scene elements in complex imagery may be subject to local contrast effects which are difficult to control. In other words, their procedure discourages *overall* judgements of the reproduction.

To avoid the possible pitfalls just described, we have designed our experiment in the following way:
1.) The experiment allowed only for a "A is better or worse than B" response from the subject (analogous to the "match/nomatch" judgements involved in color matching experiments). This *forced choice* type of experiment avoids the problem of an observer making a subjective judgement of luminance magnitude. We actually compared different luminance mappings in a psychophysical experiment to see which provided the best, overall reproduction.
2.) Since we did not want subjects to be biased by the content or composition of the image, work was done to *randomize* images for this study. Another consideration in choosing random images is that particular scene elements are not likely to divert the subject's fixation (attention) from the task of judging overall tone reproduction.

Methods

Imagery

The experiment required imagery that is representative of that seen in CEPS. EIKONIX test images were chosen that represent high-key, low-key, normal and high contrast images. These images were then made monochrome and randomized using an algorithm described by Gonsalves, Lianza, and Masia (1979). A random image is created by an iterative phase randomization and histogram equalization technique that matches the power spectrum and probability density function of the input image to the output image. More specifically, we Fourier transformed an image into its power and phase spectra (using a 2-dimensional Fast Fourier Transform algorithm based on Cooley and Tukey's, 1965), randomized the phase and backtransformed. We iteratively transformed the random image to the frequency domain, matched the power spectrum to that of the original image and backtransformed. Figure 1 is a flowchart of this procedure. Several iterations yield an image that has no visual content, but has approximately the same luminance histogram as the original.

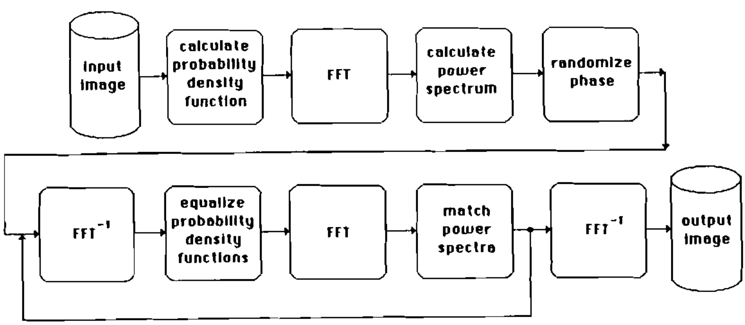


Figure 1
Flowchart of Randomization Algorithm

Other techniques for producing random textures of a given luminance histogram have been described by Cross and Jain (1983) and Haruyama and Barsky (1984). These techniques however were designed to *create* random images, and not to randomize existing ones. It would have been possible to create a random texture, and then apply a luminance histogram from a given image to it, but the intent here was to alter actual images characteristic of Graphic Arts applications.

Luminance Remapping Functions

Two remapping functions were examined, the Bartleson and Breneman brightness function, and the CIE's psychometric lightness quantity, L*. The Bartleson and Breneman brightness function is given by the following equation:

$$\text{Log}(B) = a + b*\text{Log}(L) - (g*\text{Exp}(d*\text{Log}(L)) \qquad (1)$$

Where:

- B = perceived brightness
- a = 2.037
- b = 0.1401
- L = luminance (in milli Lamberts)
- g,d = parametric constants dependent on highlight and surround luminance

We scaled brightness such that the highlight had B = 100.

The L* psychometric lightness function is also scaled to 100 and is defined as follows:

$$L^* = 116*k^{1/3} - 16, \qquad k > 0.008856 \qquad (2)$$
$$L^* = 903.3*k, \qquad k < 0.008856$$

where:

- $k = (L/L_{highlight})$
- L = luminance
- $L_{highlight}$ = highlight luminance for system

Experimental Details

35 mm Ektachrome transparencies were scanned at high resolution on an EIKONIX 8701 Image Digitizer. Except for cropping to a 512 X 512 pixel format, resulting images were then processed as facsimile images by an EIKONIX Designmaster 8000 system (i.e., no unsharp masking or other image enhancements were performed.) The image files were ported to a microVax II, where they were made monochromatic by mapping u,v chromaticities throughout the picture to .204,.318, the chromaticity of Masterproof stock

under the Graphic Technology, Inc. illuminant. The L-channel of picture data alone was then submitted to the phase randomization procedure described above. The three, color channels were then recombined and the image file was ported back to the Designmaster® 8000 to produce separation films (with the model 8601 film recorder) which were proofed by the DuPont Cromalin method.

The psychophysical portion of this experiment was performed at the Designmaster® model 8101 Preview station. The Preview console consists of a black and white monitor for menu driven i/o with the CPU, a color monitor for displaying images, and a Just color appraisal station with a Graphic Technology D5000 simulator lamp. The color monitor was calibrated such that known luminances within its range could be commanded reproducibly. Calibrations were performed with a Spectra-Pritchard 1980A tristimulus colorimeter (by Photo Research, Inc.) according to our standard protocol, which takes ambient illumination and phosphor gamma, etc., into account. The maximum and minimum luminance values reported in the Results section for monitor and proof were measured from a common image, displayed on the two media: that of the darkest neutral producible with our Cromalin system, framed by white stock or its monitor representation.

Images were displayed (both for the measurements of Lmax and Lmin, and for the subjective experiments) via the Preview software which limits the range of output to the color display to that attainable with a given hard copy output system. The software can perform further remapping to compensate for inherent differences in maximum luminance between monitor and proof which are the subject of this investigation. The remappings can also adjust for differences in dynamic range which result from ambient operating conditions. Accordingly, luminances commanded for the monitor display of random images were remapped (within the Preview software) by the brightness functions described above for psychophysical comparisons. The details of the luminance transformations will be discussed with the relevant results.

To judge the remappings, a subject was seated at the console with a hardcopy proof of one of the random images placed in the color appraisal station, and shown the same image on the monitor through the two luminance transformations. The subjects were six males ranging in age from 30 to 46. They had no advance knowledge of the details of the experiment, such as the nature of the remapping functions or images. A proof was placed in the color appraisal station and the corresponding image was brought up on the monitor with one of the two mapping functions. The subject was then asked to view and compare monitor and proof. The subject could request a change from one transformation to the other at will, not knowing which was which, or which one (L* or the Bartleson and Breneman brightness function) came up first. When satisfied, the subject then reported which mapping was better for tone reproduction. Each of the four images were viewed twice, but not in succession, to check for consistency. The luminance levels prevailing on monitor and appraisal station are not high enough to disturb levels of light adaptation (Bartlett, 1965). Thus subjects were allowed to look immediately from proof to monitor.

Results

Figures 2 and 3 show the monochrome and randomized versions of the normal and high contrast images. Five iterations of the randomization algorithm were used for these results. Figures 4 and 5 show luminance histograms pre- and post-randomization for the images in figures 2 and 3, respectively.

Table 1 shows the minimum and maximum luminances found for the monitor and the proofing system, as well as the values of d and g for the Bartleson and Breneman function. These values were read from figure 2 of their '67 paper for our conditions of highlight/surround luminance. For both media a white border framed the image so that the surround luminance equalled the highlight. The dynamic range of the monitor was found to be 47:1 as compared to 55:1 for the proofing system. These ranges were measured with other sources of ambient light present, that is, under conditions of the experiments. This was done to simulate a working CEPS environment.

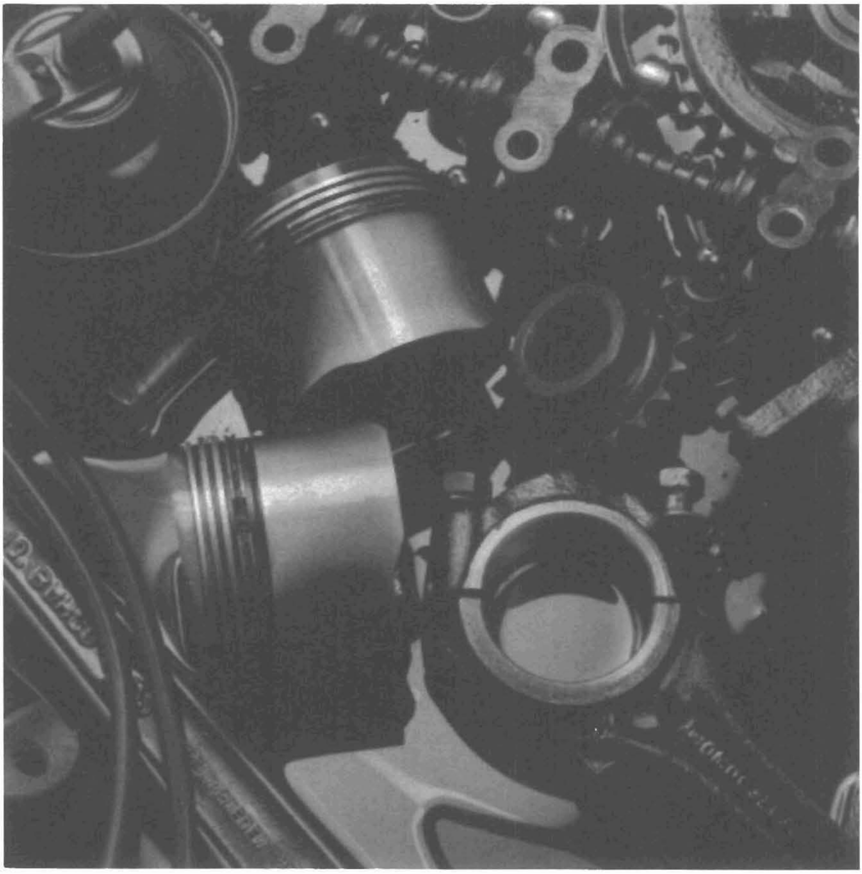


Figure 2A
Conventional version of normal image

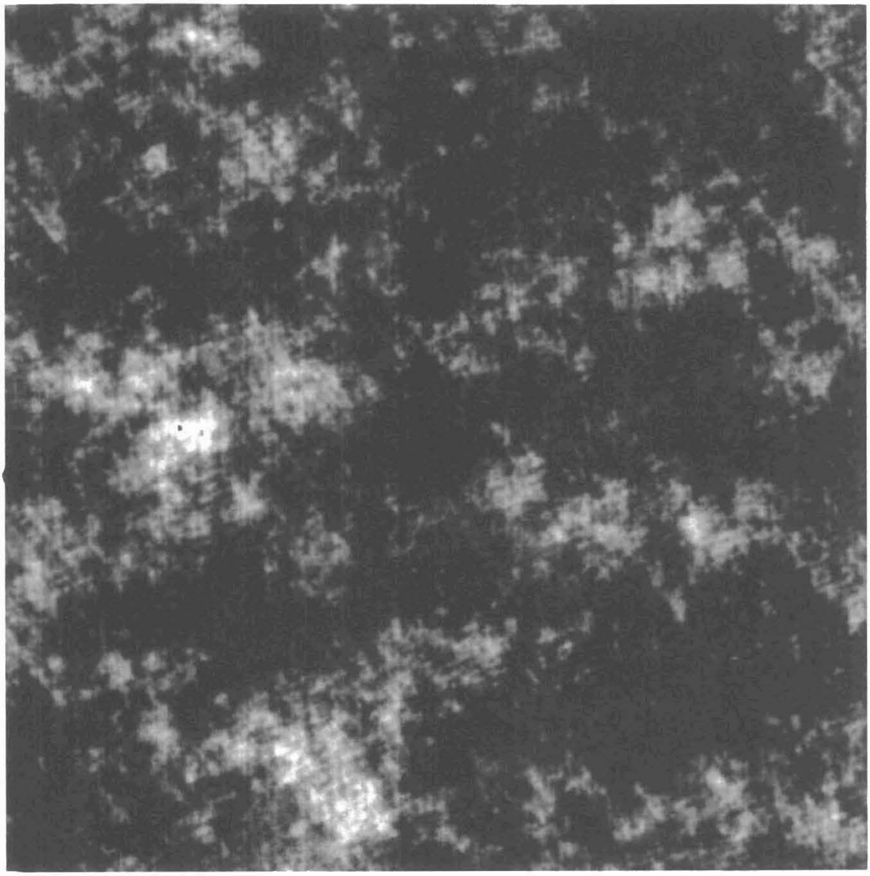


Figure 2B
Randomized version of normal image

Figure 3A
Conventional version of high-contrast image

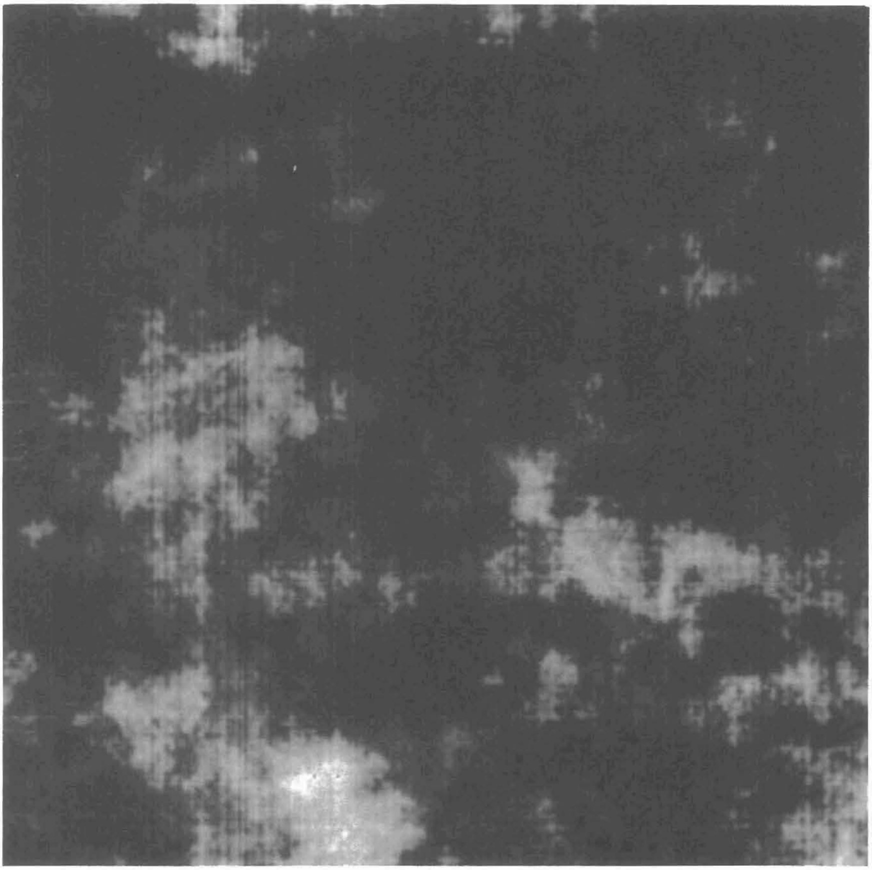


Figure 3B
Randomized version of high-contrast image

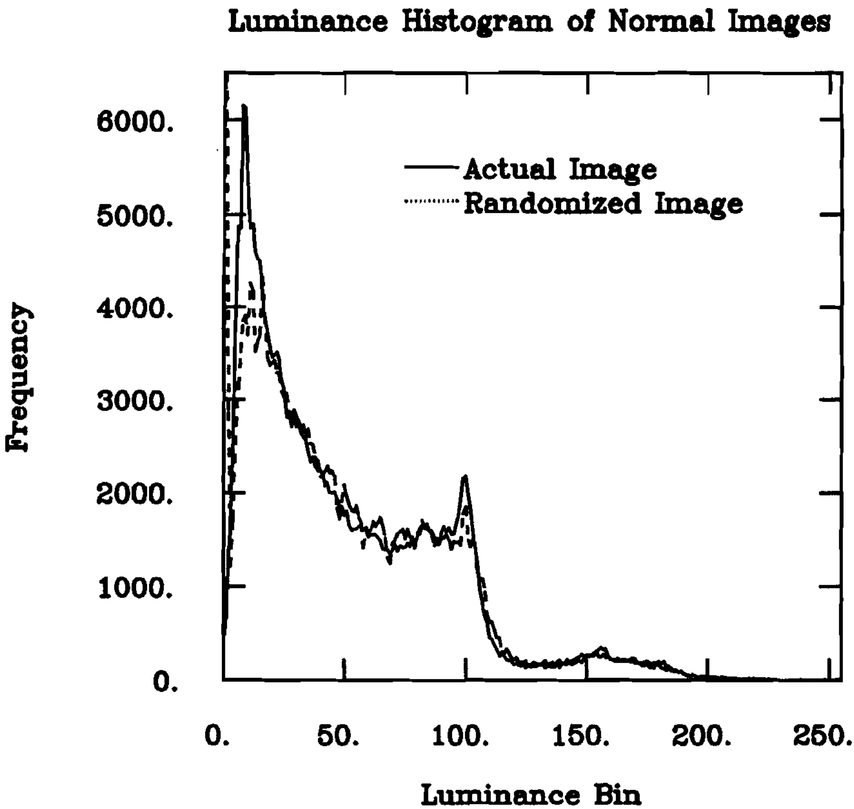
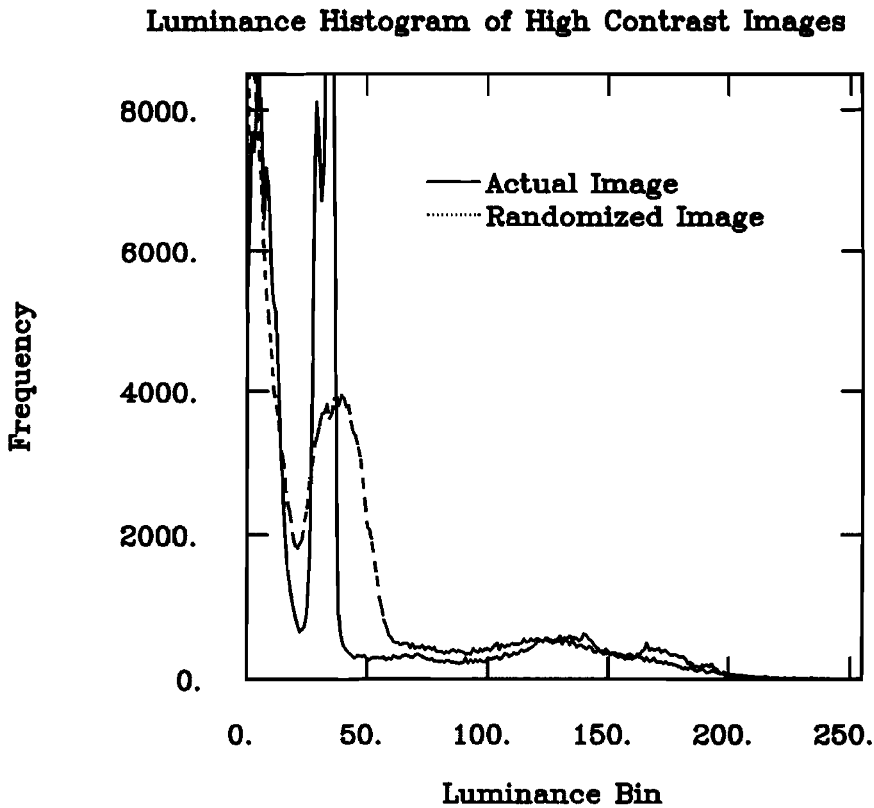

Luminance Histogram of Normal Images
6000.
5000.
4000.
3000.
2000.
1000.
0.
Frequency
Actual Image
Randomized Image
0.
50.
100.
150.
200.
250.
Luminance Bin

Figure 4



Luminance Histogram of High Contrast Images
8000.
6000.
4000.
2000.
0.
Frequency
Actual Image
Randomized Image
0.
50.
100.
150.
200.
250.
Luminance Bin

Figure 5

	L_{max}	L_{min}	d	g
Proof	126.8	2.32	-0.2943	2.4
Monitor	53.8	1.14	-0.282	2.138

Table 1
(All luminances are in milli-Lamberts)

Figure 6 shows Bartleson & Breneman-brightness and psychometric lightness (L^*) vs luminance for monitor and proof. Were those curves to be plotted in double-log coordinates, the L^* function would be a straight line with a slope of 1/3 and the Bartleson-Breneman function would be a line of slope .14 near the highlight with curvature toward the abscissa in the shadows. This is the "exponential decay" from a simple power function described by those authors. Since the parameters of the decay depend on highlight luminance, the curve for the proof diverges more toward the abscissa than that for the monitor. Thus, regardless of dynamic range, a given, normalized luminance will produce a lower perceived brightness for the medium of higher L_{max}. This implies that achievement of the same relative brightness in the shadows on the medium of lower L_{max} would require remapping of the corresponding luminance to a lower value. We will show that this is true once we have discussed the construction of remapping functions for brightness and psychometric lightness. The other point of note regarding figure 6 is that the psychometric lightness curves for the two media are coincident except for the slight difference in dynamic range.

Bartleson and Breneman did not describe a technique for transforming from one output system to another, that is, of methods for constructing luminance remappings which furnish constant relative brightness. Presumably, this is due to the fact that they could not address and modify the luminances of scene elements individually. To make such a construction, one might be tempted to convert the luminance from one system into brightness, then backtransform that relative brightness into the second system's luminance. This will work only if the two systems have exactly the same dynamic range. Otherwise, the

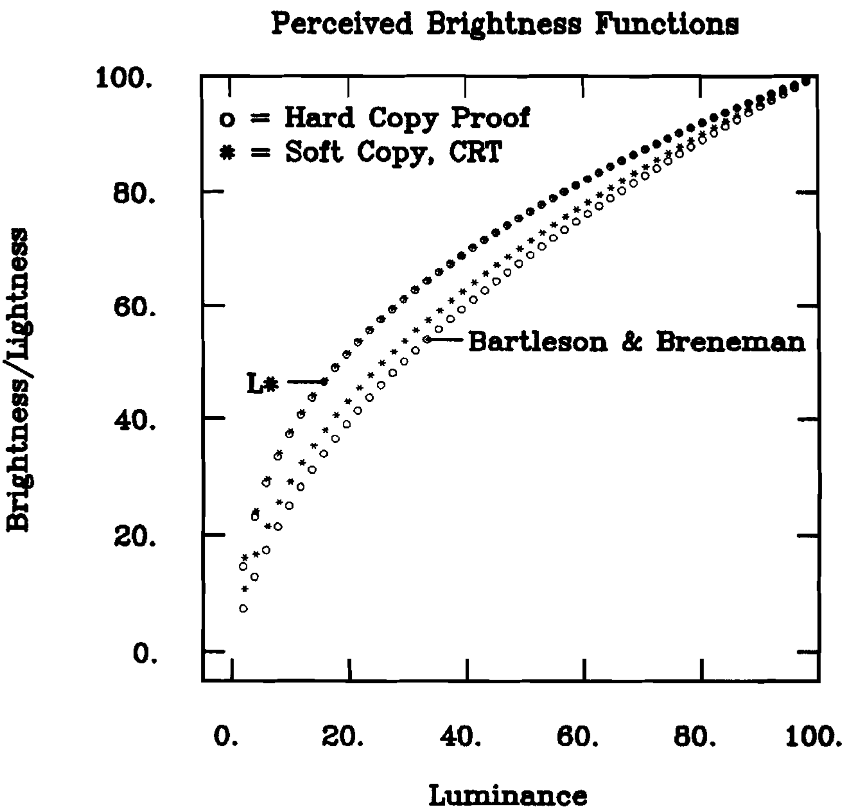

Perceived Brightness Functions
o = Hard Copy Proof
* = Soft Copy, CRT
L*
Bartleson & Breneman
Brightness/Lightness
Luminance
0.
20.
40.
60.
80.
100.

Figure 6

remapping will be undefined for critical values in the shadows.

We addressed this problem by creating a transform from the brightness function of one system to the other, fixing the minimum brightness levels, and the maximum brightnesses, and plotting a line in between, as shown schematically in figure 7. Thus to remap a luminance from system one, it is converted into a brightness for that system, then that brightness is transformed into a brightness for system two and backtransformed into a realizable luminance for system two. This technique was also used to remap in L* space. Figure 8 shows luminance out (monitor) vs. luminance in (proof) remapping functions generated in this way from Bartleson-Breneman brightness and psychometric lightness. The brightness function shows the concave-upward form predicted above; the lightness function is very nearly linear. These are the two transformations additionally applied by the Preview software for the psychophysical comparisons with actual proofs. The results of these comparisons are discussed next.

Image Type	L*	B
High Key	5	7
Low Key	11	1
High Cont	11	1
Normal	11	1

Table 2

Table 2 shows the preference for the remapping as a function of image type. The results show that the L* mapping was prefered in the DM8000 environment, although neither remapping was considered completely satisfactory. The high key image was split between L* and the Bartleson and Breneman function (labelled B in the table) with only one subject being inconsistent between trials. All of the subjects commented on how difficult the high key image was to evaluate, perhaps because the two remappings differ little in the range of luminance most heavily represented in the image. Three of the subjects were inconsistent between trials; however, only one was inconsistent on as many as two of the images. The latter was aware of his inconsistency with respect to one of the images.

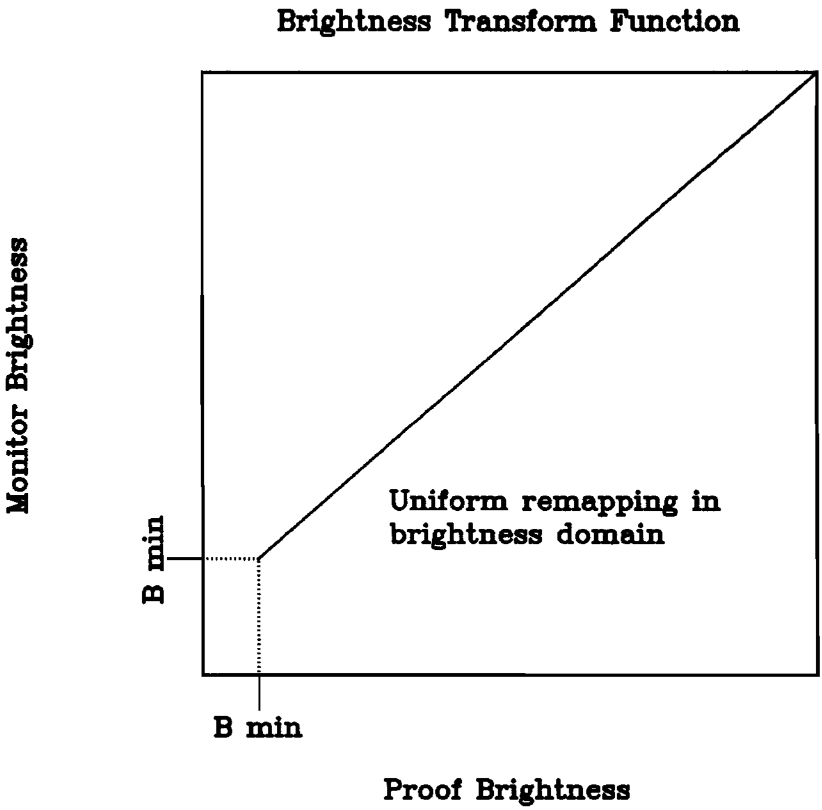
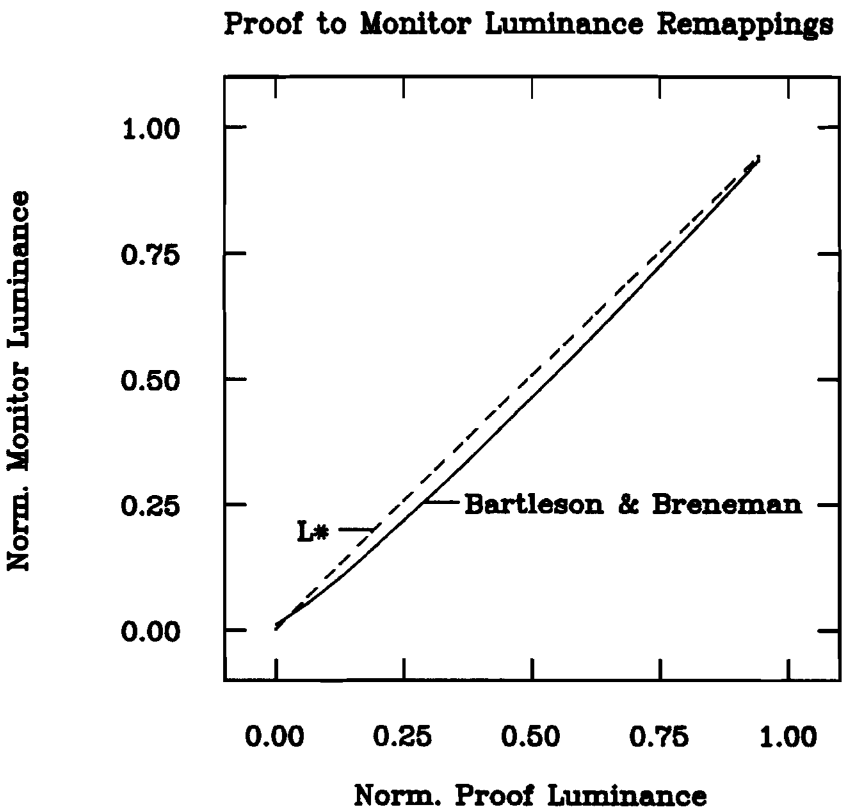

Brightness Transform Function
Monitor Brightness
B min
Uniform remapping in
brightness domain
B min
Proof Brightness

Figure 7



Proof to Monitor Luminance Remappings
Norm. Monitor Luminance
1.00
0.75
0.50
0.25
0.00
L*
Bartleson & Breneman
0.00
0.25
0.50
0.75
1.00
Norm. Proof Luminance

Figure 8

Judgements were evoked on the unrandomized versions of the images in parallel with the main experiment, with essentially identical results. Some subjects observed that the randomized images gave them "nothing to latch onto," supporting the notion that the use of randomized imagery encouraged global evaluation of monitor/proof match.

Discussion

Bartleson and Breneman empirically found a transfer function from luminance to perceived brightness for complex scenes. The CIE 1976 L* psychometric lightness function also based on empirical data, was intended to do much the same thing. What neither group of authors explicitly addressed was using those brightness quantities to do accurate tone reproduction. This study presents a technique for using their data to determine a luminance remapping to transfer from one tonal system or output medium to another.

Our experiment in particular dealt with two media where the dynamic ranges were almost the same. In the case where they are radically different, the transfer from one system's brightness to another might sufficiently distort the brightness remappings such that no tonal similarity is found. If this were the case, the output system would probably not be adequate to represent the input anyway.

The results show the L* mapping to be prefered with most images, although all subjects felt that both remappings were deficient in various ways. By iteratively modifying the luminance remappings which are paired psychophysically one could, by successive approximation, home in on the *best* luminance remapping function. Because the high key image was split between the two, perhaps the next iteration should compare L* to a variant of L* that curves towards the Bartleson and Breneman function. This second evaluation might use more high key images since these were found more difficult to evaluate.

The psychophysical paradigm employed yielded consistent results. It is worth noting that it grew out of another procedure in which subjects were given paired ten-second viewings of proof and monitor with the two remapping functions. The latter method was very time-consuming, initially yielding inconsistent data. This is probably because subjects were learning the task and establishing a criterion during the first trials. The approach adopted allowed the subjects to set criterion in a more time-efficient manner.

With the advent of remote soft proofing, in which an art director in one city wishes to preview hard copies generated in another, improvements in monitor/proof agreement are a growing concern. We acknowledge that a luminance remapping can be best only in some average sense and that the exact form may depend on the media, as well as image characteristics such as high-key, low-key, etc. In this paper we have been concerned with finding a good methodology for defining luminance remapping functions for soft proofing devices in CEPS.

Acknowledgments

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