

Preferred Tone Reproduction of Images on Soft Displays

S. Triantaphillidou, R.E. Jacobson and A.M. Ford

Imaging Technology Research Group

University of Westminster

Watford Road, Harrow HA1 3TP, UK

e-mail: triants@wmin.ac.uk, jacobsr@wmin.ac.uk, a.m.ford@wmin.ac.uk

Abstract

A series of psychophysical experiments have been carried out to investigate the preferred subjective contrast of displayed images. The contrast of the displayed images was evaluated with the use of a *gamma model* which involved cascading the gamma values of the individual components of the imaging system. The preferred contrast was found to be scene dependent and varied between 1.56 and 1.96 when images were viewed in total darkness. Probit analysis on the distributions of preferred gamma values showed that the probits of those scenes which had extremes in contrast were outside the confidence limits of other more representative scenes. The validity and implications of applying the gamma model to determine the tone reproduction of an imaging system has been investigated.

Introduction

Tone reproduction is one of the most important dimensions of image quality, being a critical component of the subjective impression of both the excellence of an image and the fidelity of a reproduction. Other important aspects of image quality, such as colour and perceived sharpness, are governed by the contrast of an image and their subjective evaluation relies on optimum tone reproduction¹. Early studies in analogue imaging systems have shown that the relationship between subjective preferred tone reproduction and objective tone reproduction varies with the viewing conditions. These include the ambient illumination, the background colour of the display, the colour of the surrounds and the angular subtense of the observer²⁻⁴.

The tone reproduction of an imaging device is evaluated by a transfer function which describes the relationship between the input and the output events. For example, the evaluation of the tone reproduction of a Cathode Ray Tube (CRT) computer display system is based on the non-linear relationship between input voltage (or the pixel values in the frame buffer, linearly converted to voltages) and the output luminance produced on the CRT faceplate. Most commonly, this relationship is described by the *gamma model*⁵⁻⁸ in equation (1):

$$\frac{L}{L_{\max}} = o + g \times \left[\frac{V}{V_{\max}} \right]^{\gamma_d} \quad (1)$$

where L is the output luminance, V is the input voltage, o and g are the offset (brightness) and gain (contrast) of the system, and the exponent γ_d describes a non-linearity in the contrast of the image. On a correctly adjusted display, the offset and gain of the system should be 0 and 1 respectively, leaving γ_d as the sole descriptor of the tone reproduction. It has been shown that the gamma function is not always valid, especially at low levels of luminance⁸⁻¹⁰. More complex models than the gamma function have been proposed to describe non-linearities of the CRT. However, the gamma model is widely used because of the simple way that *gamma-correction* can be used to compensate for the non-linearities in the system.

Similar transfer functions to that of the CRT display system, which also involve gamma as a descriptor, exist for every component of an imaging chain. For scanning devices the transfer function can be described as follows:

$$\frac{PV}{PV_{\max}} = T^{\gamma_s} \quad (2)$$

where PV is the generated pixel value and T is the measured transmittance (or reflectance) of the original photograph. In the same manner, the normalised scene luminances and the normalised output pixel values describe the transfer function of digital cameras.

The relationship between the original scene reflectance and the final reproduced luminance characterises the tone reproduction of the entire digital imaging chain, with a CRT output. The gamma function can be used as a model, and gamma as a descriptor of the overall tone reproduction of the system, provided that gamma values of all the imaging components of the chain are known. Early visual tests in photography and television have shown that the optimum tone reproduction, expressed by the overall system gamma, departs from unity and is related mainly to the environmental conditions, and in particular to the surround, which affects the perceived brightness of the image^{2,11}. Little work has been published on the preferred overall

gamma value of digital images reproduced on display systems. Nevertheless, the results mentioned above have generally been assumed to be valid in digital imaging systems. Additionally, scene content, fashion and personal preferences of image contrast have also been shown to affect the optimum tone reproduction of images¹². The purpose of this work is to investigate the preferred subjective tone reproduction for a digital imaging system, with an output on a Cathode Ray Tube (CRT) display.

Experimental

General settings

The gamma model was implemented for the determination of the overall gamma value of the reproduced images. To adjust the overall gamma to the required value, gamma-correction was applied either during acquisition, by altering scanning parameters, or to the pixel values of an image with appropriate software. The monitor used was a 15" NEC MultiSync 4FGe, calibrated to approximate the CIE standard illuminant D_{65} , driven by an Apple Macintosh graphics card, configured to display 8 bits/channel. The resolution of the screen was set to 832 x 624 pixels, at a refresh frequency of 75 Hz. The measured white and black point luminances were 204 and 1.8 cd/m^2 respectively. The greyscale transfer function was evaluated by measuring the luminance of grey patches, using a Minolta *Chroma Meter II* colorimeter. Grey patches at 15 pixel value intervals, ranging from 0 to 255

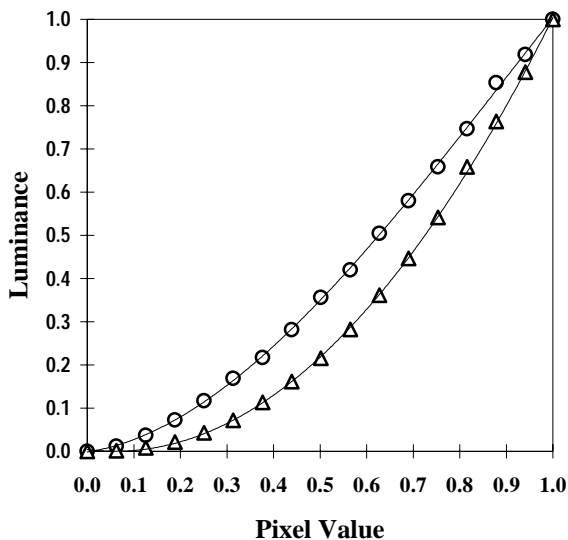


Figure 1: CRT transfer functions for Mac Standard Gamma, - O -, and Uncorrected Gamma settings, - Δ -.

and occupying 50% of the screen were displayed in the central area of the faceplate while the surrounding area

was set to display the opposite pixel value. Gamma was determined from equation (1). The offset and gain were 0 and 1 respectively in all cases, because the display had been previously correctly configured¹³. The gamma value of the display system was 1.60 when the *Mac Standard Gamma* setting was chosen (the setting used in this work) and 2.25 with the *Uncorrected Gamma* setting. (The Macintosh operating system applies a partial gamma correction of approximately 1/1.45 when the *Mac Standard Gamma* setting is selected. This gamma correction is not applied in the *Uncorrected Gamma* setting¹³). Figure 1 shows the transfer functions of the display for the two different control panel settings. The evaluation of the display transfer function and gamma was repeated at weekly intervals during the experimental period. These measurements resulted in the same gamma values of 1.60.

The display system was allowed to warm up for a period of at least ninety minutes before commencing any experiments⁹. A paired comparison procedure was adopted in which two images were displayed side-by-side in a random left/right position and a random sequence, on a mid-grey background. This ensured that images were not always presented in the same side of the display. The paired comparison method was not performed in its complete form¹⁴, because the total number of comparisons (210 pairs at least in our case), would be too high for the observers to handle. The pixel value of the background was assigned to 160 which corresponded approximately to the 50% luminance level. The colour surrounding the computer monitor was black. The observers were asked to sit at a comfortable viewing distance in front of the monitor. The viewing distances were measured after each session and found to be between 50 and 62 cm.

Preferred greyscale contrast

Initial investigations involved comparisons of 40 computer generated 17-step greyscales (136 x 436 pixels) with different values of gamma, ranging from 1.00 to 3.00 at 0.05 intervals, using a panel of fifteen observers. The observers were asked to select the greyscale which showed the most regular spacing of the steps from black to white. The overall system gamma was calculated as follows:

$$\gamma_o = \gamma_d \times \gamma_c \quad (3)$$

where the subscripts o , d , and c refer to the gamma values of the system, display and correction. Gamma-correction was performed in software in 8-bit/channel integer space. Subjective tests were carried out under the typical level of illumination in offices³ of 320 lux and also in total darkness. The results from this first experimental approach were as follows:

Under an illumination level of 320 lux: the mean value for the preferred overall gamma was 1.70, well above the published gamma values for television images and printed images viewed under room lights^{3,15}. The standard deviation was 0.43, an indicator of a wide range of preferences. With a dark surround: the mean value for the preferred overall gamma was 2.00. As expected, it was higher than that for 320 lux, but also higher than that for viewing slides and motion picture film in the darkness^{3,15}. The standard deviation was 0.40.

The results show a similar trend to the earlier work in analogue systems, with preferred gamma rising as the ambient illumination falls. However, the actual gamma values were higher than expected. The results indicate that the display of greyscales might not be a suitable way for judging the contrast of displayed images. This is partially because they are artificial images with no point of reference for observers to base their judgements. Observers stated that they had difficulties in estimating the regularity of the grey steps. Also, many observers reported that they concentrated mostly on the dark end of the scale and not on the light end.

Images of greyscales also were poor subjective test stimuli, possibly because of the physical differences they have with images of 'real scenes'. Psychophysical research has shown that physically identical luminous areas, containing small luminous gradients, as is the case for real scenes, are different in brightness than when they are separated by luminous steps, as is the case for greyscales¹⁶. Also, simple field images have been shown to have higher preferred contrast than complex field images¹¹.

Preferred scene contrast

Additional experiments were carried using an analogous procedure but involving images of real scenes, captured on Agfa Scala 200 ISO black-and-white transparency film, followed by digitisation via scanning. Kodak Q-13 greyscales were captured at the end of each roll of film and the gamma value of the photographic system was evaluated from the straight-line region of the characteristic curve¹⁷. Greyscales were also included in some of the selected scenes for scanning. Scanning was performed using a Nikon 35 mm LS-1000 SuperCoolscan in a 12 bit/pixel space, while the acquired images were stored as 8-bit/pixels image files. The 12-to-8 bit conversion was performed by the scanner. The tonal characteristics of the scanner were previously investigated using the Kodak Q-60 Colour Input Target on Ektachrome slide film, as well as from the Kodak Q-13 greyscales recorded on the Agfa Scala slides. The transfer functions for the various nominal gamma settings of the scanner were plotted on logarithmic axes and gamma was determined from the straight-line region of the function. Figure 2 shows three scanner transfer functions for three different gamma settings. The overall system gamma was determined from equation (4):

$$\gamma_o = \gamma_d \times \gamma_s \times \gamma_p \quad (4)$$

where the subscripts *o*, *d*, *s* and *p* refer to the gamma values for the system, display, scanner and photograph respectively. Gamma-correction was applied during scanning to adjust the overall gamma of the final displayed image. The overall gamma values ranged from 1.10 to 2.99 at 0.09 intervals. The dimensions of the displayed images were 260 x 400 pixels. Ten observers were used during this experimental phase, which took place in total darkness. The observers were asked to choose from each pair of

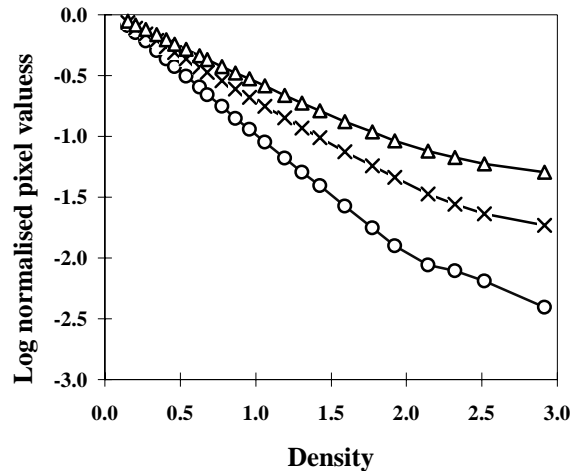


Figure 2: Nikon SuperCoolscan transfer functions for three different Coolscan Gamma settings. The gamma values are equal to 1.0, - O -, 0.75, - X - and 0.55, -Δ - and were determined from the straight-line region of the curves.

displayed images the one with the preferred contrast. Table 1 lists the test images and their descriptions.

Results for the preferred overall gamma of five scenes, carried out by 10 observers, 4 times each, are plotted in Figure 3. The mean preferred gamma values and standard deviation from the means are presented in Table 2 for each scene. The findings indicate that the preferred overall gamma value is scene dependent. This result agrees with those of Roufs et al.¹² who worked with still images displayed on television sets. Their results, however, gave preferred gamma values with a far wider range.

<u>Image</u>	<u>Description</u>
<i>house</i>	Image of a room with a person and various objects. Half of the frame is lit by bright light. The other half is in shadow.
<i>mount</i>	Mountain landscape with little snow and trees and a wooden house in the foreground, photographed on a bright sunny day.

<i>objects</i>	Indoor still-life with various objects varying in colours and tones, lit by natural daylight.
<i>wood</i>	Misty landscape with trees and a wooden bench in the foreground.
<i>angel</i>	Indoor portrait of a woman with Oriental complexion, lit by natural daylight.

Table 1: Description of test images used.

Furthermore, from Table 2 it can be seen that some scenes had higher standard deviations than others. The *objects* scene, for example, which is a still life scene whose histogram showed an equal distribution of tones had a mean preferred gamma of 1.68 and a small standard deviation of 0.07. However, natural scenes (such as *mount*, *house* and *wood*), whose histograms tend to fall exponentially at high luminances¹⁸, had a much higher standard deviation. Also the overall mean value of the preferred gamma for these three natural scenes was found to be 1.64.

Image	Mean preferred gamma	Standard deviation
<i>house</i>	1.56	0.13
<i>mount</i>	1.58	0.14
<i>object</i>	1.68	0.07
<i>wood</i>	1.76	0.20
<i>angel</i>	1.96	0.21

Table 2: Mean preferred gamma values and standard deviations for five scenes.

House, a scene which contained much more shadow than highlight information, was found to have the lowest preferred gamma of 1.56. This result suggests that the reproduction of low key scenes is preferred with lower contrast. This may be due to the fact that on increasing contrast the black areas of the reproduction also are increased, i.e., the reproduced image becomes too dark. Probit analysis¹⁹ was performed on the distributions of preferred overall gamma values for the total number of observations. The probit lines indicated that the *house*, *mount* and *object* had similar distributions within a 95% confidence limits. *Wood* and *angel* were outside the 95% confidence limits of the three previous scenes. However, these two scenes had extremes in contrast. *Wood* is a low contrast scene (misty landscape) whereas *angel* is a high contrast portrait having a bimodal histogram.

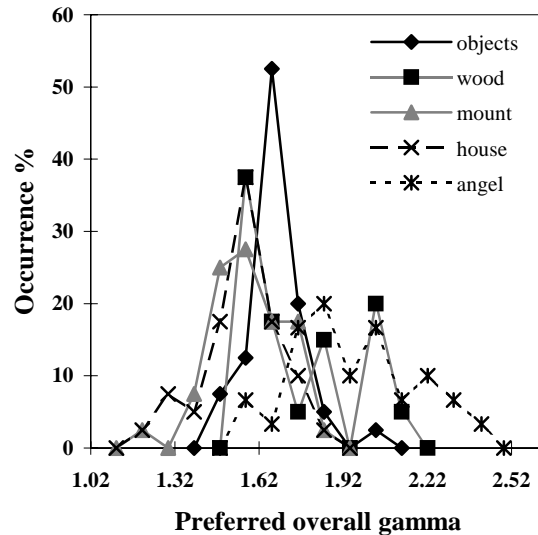


Figure 3: Preferred gamma for five different scenes.

Linear brightness reproduction

It has been shown by Bartleson *et al.*¹¹ that the aim of the tone reproduction of an imaging system is the linear reproduction of relative scene brightness. Initial experiments, using one of the test-images (*objects*) and the achromatic correlate of brightness, Q , introduced in Hunt's Colour Appearance Model²⁰ showed that the relative brightness of the preferred image matches the relative brightness of the original scene. This result suggests that, using a colour appearance model and subjective results from one set of viewing conditions, it is possible to predict the optimum subjective tone reproduction of displayed images for various environmental conditions and different display systems. Further investigations are taking place to test the above concept for different scenes under various display conditions.

Problems applying the gamma model

Gamma and digital acquisition devices

It is known that in photography, the gamma descriptor of contrast does not take into account the 'toe' and 'shoulder' regions of the characteristic curve but only the straight-line region of the function¹⁷. This implies that the entire tone reproduction function cannot be described by only one variable. Similarly, in CRT display systems, gamma does not describe the transfer function of the system with enough precision. In digital acquisition devices gamma is also an incomplete measure of the transfer function. Figure 4 shows the monochrome transfer function of a Kodak DCS420 digital camera, plotted on logarithmic axes. It appears that the tone reproduction function is very similar to the photographic characteristic curve, where the tones are

compressed at the toe and the shoulder of the function. Determination of the tone reproduction of scanning devices using the gamma descriptor presents equal difficulties. As with digital cameras, there is a distortion at the ends of the transfer function which can be seen in Figure 2. In addition, in many photographic scanners, the transfer function applied to the scanned data is dependent in some way on the statistical properties of the data. This implies that images with different mean densities, but scanned with identical scanner settings, will have different tone reproduction characteristics and therefore different measured gamma values.

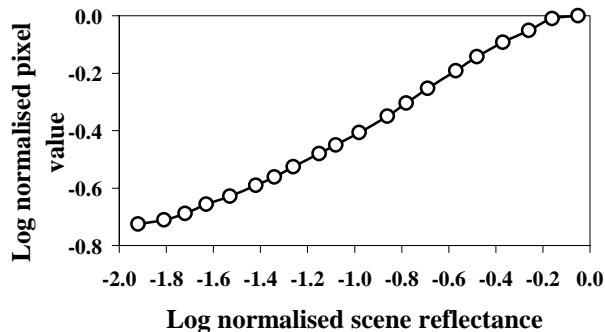


Figure 4: Monochrome transfer function for the Kodak DCS 420 digital camera. The gamma measured from the straight line portion of the function is 0.45

In the above examples, gamma has been shown to be a poor descriptor of the transfer functions of digital acquisition devices. The need for more parameters describing the transfer curves is obvious, such as the photographic contrast index ($C.I.$) or \bar{G} which although they relate to gamma, are more rigorous descriptors of image contrast¹⁷.

Gamma correction and grey level loss

Even if we assume that the gamma model performs relatively well, there are further problems associated with tone modification operations in the limited precision integer mathematics used in digital imaging. As mentioned earlier, gamma-correction is employed to adjust the overall gamma of a digital imaging system to an optimum value. The problem with gamma-correction is that in discrete systems there is a loss in grey levels due to rounding errors²¹. For example a gamma correction of 0.5 results in a 25% loss in the number of grey levels. In a 12-bit/channel system, this loss is not very significant, because there are many more grey levels to describe the luminance range of the system. In an 8-bit/channel system, however, the total number of grey levels is 256 and 25% corresponds to 64 grey levels lost. Performing gamma correction in 12-bit/channel space and then down sampling the gamma-corrected signal to 8-bits/channel, is a usual compromise many digital acquisition

devices implement, including the scanner used in this work. Figure 5, shows the grey level loss for a range of different gamma corrections in 8, 10 and 12 bit sampling and 8 bit output.

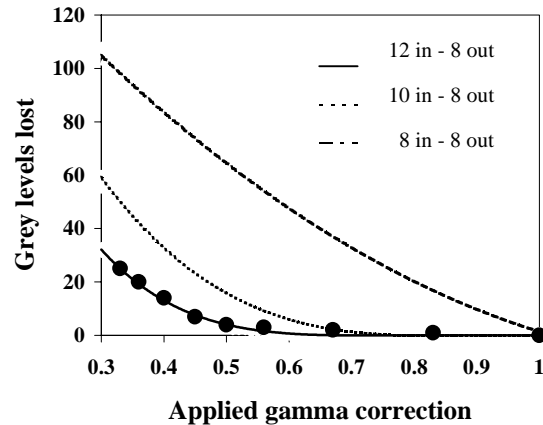


Figure 5: Grey level loss for a range of different gamma corrections with 8, 10 and 12 bit sampling and 8 bit output. The lines are for calculated values and the filled circles are measured points.

Losing a number of grey levels results in a loss in the amount of information the digital image retains. Whether this information loss introduces image quality problems depends on the definition of the visible step size within the imaging system and the relationship between luminance differences and pixel differences. In addition, there are changes in the micro-image contrast on certain regions of the image, which may alter the macro appearance of the reproduced tones. The tonal distortions are not described by the transfer function of the image. Therefore, the need for some description of the number of levels as well as the functional relationship describing tone may be essential.

Conclusions

The following conclusions are drawn from this work:

- Images of greyscales are not good indicators of preferred image contrast.
- The preferred gamma values of scenes reproduced on soft displays are scene dependent.
- For scenes which have extremes in contrast, there is a large variation in preferred gamma.
- The mean overall preferred gamma value for all test images on a soft display, when viewed in total darkness, was 1.70 with a standard deviation of 0.16.
- The distribution of the preferred gamma values of natural scenes, whose histograms fall exponentially at high luminances, had wider spreads than that of a scene with an equal distribution of tones.
- Gamma, is not a very precise descriptor of the transfer function of various acquisition devices.

- Grey level loss resulting from quantization errors has a detrimental effect on tone reproduction. A measure of such a loss is therefore required for a full description of digital tone reproduction.

Acknowledgement

The authors would like to thank Dr Geoffrey Attridge for helpful discussions.

References

1. R.W.G. Hunt., *CIM'98 Colour Imaging and Multimedia*, 1-8, 1998.
2. E. J. Breneman, *Photographic Science and Engineering*, 6, 172—179, 1962.
3. R.W.G. Hunt, *The Reproduction of Colour in Photography, Printing and Television*, Fountain Press, Tolworth, England, fifth edition, 1995.
4. M.D. Fairchild, *Colour Appearance Models*, Addison-Wesley, MA, USA, 1998.
5. D.Travis, *Effective Colour Displays: Theory and Practice*, Academic Press, 1991.
6. C. A. Poynton, *SMPTE Journal*, 102, 1099—1108, December 1993.
7. R. S. Berns, R. J. Motta, and M. E. Gorzynski, *Color Research and Applications*, 18, 299—314, 1993.
8. A. M. Ford, R. E. Jacobson, and G. G. Attridge, *J. Photogr. Sci.*, 44, , 23—26, 1996.
9. R. S. Berns, M. E. Gorzynski, and R. J. Motta, *Color Research and Application*, 18, 315—325, 1993.
10. W. B. Cowan, *Computer Graphics*, 17, 315—321, 1983.
11. C. J. Bartleson and E. J. Breneman, *Photographic Science and Engineering*, 11, 254—262, 1967.
12. J. A. J. Roufs, *Human Vision, Visual Processing, and Digital Display SPIE*, 66—72, 1989.
13. C. A. Poynton, *A Technical Introduction to Digital Video*, Wiley and Sons, 1996.
14. C. J. Bartleson, *Optical Radiation Measurements, Volume 5, Visual Measurements*. Academic Press, New York, 1984.
15. M. D. Fairchild, *Color Research and Application*, 20, 352—363, 1995.
16. G. R.. Lockhead, *Behavioral and Brain Sciences*, 15, 543—601, 1992.
17. J. Eggleston, *Sensitometry for Photographers*, Focal Press, 1984.
18. W. K. Pratt, *Digital Image Processing*, Wiley & Sons, California, second edition, 1991.
19. D.J.Finney, *Probit Analysis*, Cambridge University Press, Cambridge, second edition, 1962..
20. R..W.G.Hunt, *Measuring Colour*, Ellis Horwood Limited, Chichester, second edition, 1991.
21. J.F. Blinn, *IEEE Computer Graphics and Applications*, 9, 100—105, 1989.