The “Which Blair Project”:
A Quick Visual Method for Evaluating Perceptual Color Maps

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ABSTRACT

We have developed a fast, perceptual method for selecting color scales for data visualization that takes advantage of our sensitivity to luminance variations in human faces. To do so, we conducted experiments in which we mapped various color scales onto the intensitiy values of a digitized photograph of a face and asked observers to rate each image. We found a very strong correlation between the perceived naturalness of the images and the degree to which the underlying color scales increased monotonically in luminance. Color scales that did not include a monotonically-increasing luminance component produced no positive rating scores. Since color scales with monotonic luminance profiles are widely recommended for visualizing continuous scalar data, a purely visual technique for identifying such color scales could be very useful, especially in situations where color calibration is not integrated into the visualization environment, such as over the Internet.

CR Categories: 3.6 [Computer Graphics] Methodology and Techniques

Keywords: Perceptual color scales, visual artifacts in visualization, Internet color, human color vision.

1. Introduction

Color scales are an integral part of visualization. Poorly constructed color scales, however, can lead to misinterpretations of the data, either by failing to capture the structure in the data, or by introducing visual artifacts. This problem has stimulated considerable interest in creating *perceptual color maps* that are based on knowledge about how humans perceive variations in hue, saturation and luminance ([3], [10], [13], [15], [16], [17], [18], [19], [25]). Users, however, are not generally aware of perceptual color maps, or of the consequences of using inappropriate color scales. Many simply use the default color maps provided by their visualization systems, even though the artifacts they can produce have been well-documented ([11], [20]). Moreover, even users who are cognizant of these issues are often discouraged from implementing perceptual color maps because to do so typically involves difficult and labor-intensive display calibration. Furthermore, in some cases, such as in an Internet environment, calibration is impossible because the color characteristics of the output device are often not known. To make matters worse, existing methods for evaluating color maps usually involve rigorous, time-consuming psychophysical procedures.

The goal of this paper is to develop a method that reduces these costs, thereby making perceptual color maps more accessible to users of visualization systems.

2. Using Visual Judgments to Calibrate Electronic Imaging Systems

Recently, several papers have appeared in which visual judgments are used to calibrate display monitors. In these methods, human observers make visual judgments about carefully-constructed test patterns, and these judgments are used to estimate parameters such as the display gamma (e.g., [8],[12]).

In the same vein, we have developed a method that uses visual judgments to evaluate color scales. Since there is considerable consensus in the field that color scales that increase monotonically in luminance are good candidates for faithfully representing the magnitude of continuous data ([10],[11],[13],[18],[20],[21]), this method is designed to quickly identify scales that include a monotonic luminance component. To do so, we use a digitized photographic image of a human face as the test pattern. Since a photograph of a face provides a structured visual pattern with gradual variations in luminance across its surfaces, it is particularly well suited for identifying irregular variations in the luminance of color scales.

Previous studies in the vision literature have suggested that human observers are very sensitive to luminance variations in images of human faces. For example, when an isoluminant color scale is applied to a digitized photograph of a face, the ability to make out the structure is greatly reduced because it doesn’t provide enough luminance contrast to the channels responsible for processing high spatial-frequency information ([24]). Cavanagh [4],[5] has shown that faces are difficult to recognize when luminance modulations change the darkness of shadows, causing them to be misinterpreted. Roufs [22] has found that the perceived quality of digitized portraits depends on the luminance intensity function, or gamma, with which it is displayed. These findings suggest that a face stimulus might be very effective in revealing luminance non-monotonicities.

3. Perceptual Rating Experiments

In this paper, we describe experiments where we map several color scales onto the intensity values of a digital photograph, an measure the naturalness of these images. We then analyze these results with respect to the luminance characteristics of these color scales. For these experiments, we selected the face of Tony Blair, and have come to call this work the "Which Blair Project".

The idea behind this design is as follows. If a color scale contains a monotonically-increasing luminance component, an image that is pseudo-colored with that color scale should preserve the relative brightness variation of the original photograph. If a color scale does not include a monotonically-increasing luminance component, the relative brightness variation in the photograph will not be preserved, and the pseudo-colored face will look unnatural or distorted. The degree of distortion should be proportional to the departure from luminance monotonicity. By testing color scales with different luminance profiles, we were able to examine these luminance effects more closely.

3.1 Stimulus Materials

3.1.1 The Tony Blair Stimulus

Figure 1 shows two histograms of the data values in the digitized photograph of Tony Blair. The first histogram shows the distribution of data values for the entire photograph. The large peak in the center of the range represents the data values or the uniform background. The second histogram shows the distribution of data values when the background is removed. Data values for the face span the range from 0 to 255 in a flat, smooth, uniform manner.

3.1.2 Eight Color Scales

Figure 2 (shown in the accompanying color plate) shows the eight color scales used in these experiments. Figure 3 shows their luminance profiles, as measured on the calibrated monitor used in these experiments. The two graphs depict data for the color maps in the first and second experiments, respectively. The luminance values from the calibration process were transformed to CIE LAB L* for reporting purposes.

The color scales in Experiment 1 were:

1.) **LAB Grayscale**: a monochrome color scale in CIE-LAB color space, with linearly-increasing L*, and constant a* and b*. L* is designed to be linear in perceived luminance and corresponds to a luminance scale in which L (in cd/m^2) increases exponentially, with an exponent of 3 .0.

2.) **Heated Body**: a color scale in HSV color space, with linearly increasing value (V) and smooth hue variation from red to yellow. On our monitor, this color scale increased linearly in luminance, and thus, in L*, displays the classic compressive function.

3.) **LAB Isoluminant Rainbow:** a spectrum scale in CIE-LAB, with hue varying in spectral order from blue through red, with fixed luminance and saturation. This scale was designed to be a rainbow-like scale, but without any luminance variation across its range.

4.) **Rainbow:** a spectrum scale, interpolated linearly through the saturated, spectrally ordered hue points: blue, cyan, green, yellow, and red in RGB. The default standard in many visualizations systems, this color map has an inverted W luminance profile (see Figure 3). Although not monotonic in luminance across its entire range, we there are regions where luminance increases monotonically.

The color scales in Experiment 2 were:

1.) **HSV Grayscale:** a grayscale color map in HSV that is linear in V (nearly exponential in L; nearly linear in L*) and constant in H and S. .

2.) **HSV Decreasing Saturation:** a scale in HSV that decreases linearly in S ("saturation"), with constant H and V. In this color map, luminance also increases mnotonically..

3.) **HSV Increasing Saturation:** the mirror image to the color scale above, however, since S increases, luminance decreases.

4.) **LAB Isoluminant Saturation:** is a color scale in CIE-LAB with increasing saturation, fixed luminance and fixed hue. This color map does not vary in luminance, or in L*.

3.1.3 A Color Map Family For Each Color Scale

We normalized the range for each color scale to [0-99], and created from each seven additional scales, each subtending 25% of the entire range. The seven overlapping quarter ranges were [0-24], [12-36], [25-49], [37-61], [50-74], [62-86], and [75-99]. We then mapped each of these 64 color scales (eight full-range and 56 overlapping quarter-ranges) onto the data values of the digital photograph.

Figure 4 shows the family of eight LAB luminance scales, and how these scales looked when applied to the Tony Blair photograph. The image to the far left shows the photograph represented with the full range color scale. The next seven images in the row show each of the sub-segments mapped onto the photograph, increasing, in order. Using this same format, Figure 5 (see color plate) shows the eight color scales and resulting images for a) the Rainbow map and b) the HSV Saturation Decreasing map (with monotonically increasing luminance).

Of this set of 64 scales, 34 had monotonically increasing luminance profiles, 16 had no luminance variation at all, 10 had monotonically decreasing luminance profiles, and 4 varied non-monotonically in luminance. Thus, the set contained color scales with increasing, decreasing, fixed and mixed luminance variation.

In the data analysis, data for the [0-24] range for the HSV Increasing Saturation scale were not reported, owing to an error in the construction of this stimulus.

3.1.4 Observers

The experiments were conducted in two sets, one for each group of four scales. There were 8 observers for the first set (six males and two females) and 9 observers for the second set (seven males and two females) and did not include the authors. All observers were drawn from the research population at the IBM T.J. Watson Research Center. All had normal, or corrected-to-normal vision.

3.2 Experimental Design

In each session of the experiment, a matrix of 32 pseudo-colored face images, generated from the 32 color scales, was presented to the observer on a calibrated IBM P202 color display monitor. The images were arranged in a grid of eight rows by four columns. The 32 pictures were arranged in a different random order for each observer, for each session. At any one time, the observer could see 6 rows, and could scroll to view the remaining stimuli. The observer’s eyes were approximately 15 inches from the screen, and each image subtended a visual angle of approximately 5.1 x 6.4 degrees. A 5-point rating scale was provided beneath each image. Figure 6 (see color plate) shows an example of the matrix of faces used in these experiments.

In each experiment, the subject was asked to rate each picture on a scale {-2, -1, 0, 1, 2} representing the choices {“very bad”, “somewhat bad”, “neutral”, “somewhat good”, “very good”} according to the degree to which the image appeared to be a recognizable photograph of a face. Each observer served in four sessions, and in each, rated 32 images. These judgments were very easy for the observers to make. Each session took less than 5 minutes.

4. Experimental Results

Figures 7 shows the perceptual ratings for the two experiments. For each of the color scales, we show the rating results for the full-range color scale [0-99] to the left. The remaining bars depict data for the seven sub-ranges of these color scales, [0-24], [12-36], [25-49], [37-61], [50-74], [62-86], and [75-99].

Since the ranking data from these experiments are ordinal, not interval, it is not legitimate to compute parametric statistics, such as a mean rank. Instead, for each color scale, across observers, we computed the percentage of each ranking score obtained (that is, the percentage of “2,” “1,” “0,” “-1,” and “-2” scores). In these charts, the solid bars represent the percentage of responses that were rated “good” or better (rated either 1 or 2. The superimposed unfilled bars represent the percentage of responses for which the target was considered to be at least “acceptable,” (rated either 0, 1 or 2). This method allowed us to analyze the data according to two different judgment criteria.

4.1 Luminance Monotonicity

There are clear differences between the eight color scales. The four color scales that contained a monotonically increasing luminance component (LAB Grayscale, Heated Body, HSV Grayscale and the HSV Decreasing Saturation) produced consistently positive judgments. The color scale with monotonically decreasing luminance, HSV Increasing Saturation, produced consistently low judgments. Color scales that had no luminance component (LAB Isoluminant Rainbow and LAB Isoluminant Saturation) produced the lowest judgments, and were virtually never rated higher than –1 or –2. The default color map in the industry, Rainbow, produced generally poor results. The full-range rainbow color map plus four of the seven sub-ranges received only negative ratings. For the two sub-ranges where luminance increased monotonically [0-24] and [50-74], however, ratings were very positive, especially for the [0-24] range.

Overall, color scales with increasing luminance profiles produced images that were judged to be natural and recognizable; 32 of the 34 scales with monotonic luminance profiles produced a high percentage of positive scores. More importantly, *only* those color scales with a monotonic luminance component produced images that were judged as natural.

4.1.1 Grayscale and Heated Body Maps

By examining the rating scores according to two criteria, we can get a more detailed view of these data. For the LAB and HSV grayscales color maps, the weaker criterion (open bars) shows that close to 100% of all the ranks for all conditions, for all subjects, were greater than or equal to 0. That is, for all observers, all the LAB and HSV color scales, whether full range or for a subset of the range, produced an acceptable photographic image. Looking at the stricter criterion, shown in filled bars, we see that for both color scales, the proportion of scores which were positive (1 or 2) was highest for the full-range color scale, [0…99], and dropped off monotonically as the range was shifted to higher luminance values. This suggests that the effectiveness of the color scale in representing magnitude depends not only on its dynamic range, but also on luminance contrast. For both color scales, all the subset color scales had the same dynamic range, measured in L*, but the effectiveness of that luminance difference decreased as the baseline luminance increased. This drop-off was more pronounced for the LAB scale. Although the normalized luminance profiles for the LAB and HSV color maps were virtually identical, the actual dynamic range of the HSV color map was larger, possibly accounting for this difference. In order for the LAB scale to increases monotonically in luminance and be achromatic, a small sacrifice is required in dynamic range.

At the low end of the range, the Heated Body scale produced results quite similar to the LAB and HSV scales. Looking at the more stringent criterion, however, we see that the percentage of "good" ranks (1 and 2) dropped off much more quickly for the Heated Body color scale. Some of this effect might be attributable to the compressive shape of the L* function for this color map (Figure 3), thereby contributing relatively less luminance contrast in this range. However, we see that rating performance did not drop off monotonically, and instead, increased at the top end of the range. In this region, although luminance contrast is dropping, color contrast is increasing, as the color map changes from reddish to yellowish. One possible interpretation is that the hue component of the color scales may be exercising a facilitatory influence on these judgments. Clearly, the next step in this work will involve studying interactions between hue and luminance in producing effective color scales for visualization.

The HSV Increasing Saturation scale produced images that were not ranked as highly as those created with the other monotonic luminance scales. Referring to Figure 3, we see that although this color scale did achieve 100% of its white point luminance, the lowest-luminance value in the color scale was relatively high, affecting both the dynamic range and luminance contrast of these color scales.

4.1.2 The Role of Luminance Polarity:

To explore the role of luminance polarity, we compared the HSV Decreasing Saturation scale with the HSV Increasing Saturation Scale, in the bottom row. In HSV space, variations in S produce correlated variations in luminance. We see clearly that while the HSV Decreasing Saturation scale (with monotonically-increasing luminance) produced relatively high rating scores; the HSV Increasing Saturation scale (with decreasing luminance) produced images that were poorly ranked. The decreasing luminance scale reversed the polarity of the image relative to the sign of the data. The resulting "reverse video" images did not appear natural or recognizable to the observers, even though their luminance contrast was identical.

4.1.3 The Rainbow Color Map

For the Rainbow color map, we see that although the full-range color scale produced only negative scores, there were several color scales that produced positive scores. Looking at the more stringent criterion, we see that the two ranges with monotonically increasing luminance, [0-24] and [50-72] produced a high proportion of high ranks, with the [0-24] range, from dark-blue to green, producing 100% "good" ratings. A relatively high proportion of "1" and "2" scores were also obtained for the [12-36] range (blue to green). Although the luminance profile in this range is non-monotonic, there is a very large, almost linear increase in L* in the first half of its range (luminance contrast = .56) and a mostly flat profile in the second half (contrast approximates 0). It is interesting to compare these data with those for the [62-86] scale (green to red), where luminance also increases sharply in the first half of the range, but then decreases sharply in the second half. This color scale receives no positive scores. Perceptually, the [12-36] scale may function like is as a truncated monotonic luminance scale, whereas the [62-86] scale is clearly non-monotonic. The hue variation in these color scales may add to the perceptual monotonicity of the [12-36] scale. It goes from low-luminance blue to higher-luminance green in the first half of its range, and stays at roughly the same luminance green in the second half. The [62-86] scale, on the other hand, goes from low-luminance green to higher luminance yellow, but then moves to a low-luminance red.

4.1.4 Color Scales with No Luminance Variation

The data for the Isoluminant Rainbow and Isoluminant Saturation maps clearly show that luminance modulation is required for conveying information about detailed (high spatial-frequency) spatial structure. These color maps contained no luminance modulation and produced no positive scores. Hue or saturation modulation, in the absence of luminance modulation, did not convey any information about the magnitude of the data values, and consequently did not convey any information about the spatial structure in the data.

4.2 Luminance Contrast

In the analysis so far, we have discussed the rating data in terms of the monotonicity of the luminance profiles for each of the color scales. We saw a general decrease in rating score for higher luminance color maps, suggesting the existence of an underlying contrast transducer function. To test this hypothesis, Figure 8 depicts the percentage of favorable ratings ("1" or "2") as a function of luminance contrast for all 63-color scales. We have taken L* contrast as our measure, but the graph is essentially indistinguishable if we use L, the normalized luminance values. The black symbols represent color scales with a monotonic luminance component over their entire range. The gray symbols indicate color scales with no luminance contrast. The open symbols indicate color scales with non-monotonic or decreasing luminance components. The symbol shapes indicate the color scales from which these data were drawn.

4.2.1 Contrast of Monotonic Luminance Scales

Data for 32 color scales with monotonically increasing luminance (solid symbols) show a smooth, negatively accelerated increase in performance with luminance contrast. These are data from the HSV and LAB grayscale color maps, the Heated Body color map, the HSV Decreasing Saturation Map, and the two scales from the

Rainbow map that had monotonically-increasing luminance (solid squares with a “plus” symbol). The best-fitting curve through these data is a logarithmic function (r^2 = 0.679), accounting for 46% of the variance). If the curve is recomputed including data from the 0-contrast color scales, the shape of the curve remains the same, but r^2 increases to 0.834 (accounting for 70% of the variance). This result shows that luminance contrast is a driving influence in these judgments. Across color scales, the greater the luminance contrast, the better the photographic image looks, and perceived quality increases as the logarithm of luminance contrast.

Since this is a logarithmic function, the biggest increase in the quality of the representation occurs in the early part of the contrast range; for all color maps with monotonic luminance components, once the luminance contrast exceeds 20%, over 70% of the rating scores are positive. This suggests a pragmatic recommendation for selecting a color map to represent magnitude information: use color maps that increase monotonically in luminance and have a luminance contrast in excess of 20%.

4.2.2 Other Color Scales

The gray symbols superimposed at (0,0) in this plot represent color scales with no luminance modulation, and consequently no luminance contrast. These are the Isoluminant Rainbow and Saturation scales. With no luminance variation, detailed (high spatial-frequency) information was not detectable, and was thus not effective in communicating spatial information, even when hue or saturation varied monotonically.

The open circles show data for the HSV Increasing Saturation (decreasing luminance) color maps. Data for the six Rainbow color maps that did not include a monotonic luminance component are shown in open squares, including two ranges that were monotonically-decreasing in luminance and three ranges that were non-monotonic in luminance. Although some of three of these color scales contained a luminance contrast approximating 30%, they did not produce good images, since luminance did not increase monotonically.

4.3 Summary of Results

In these experiments, observers rated the naturalness of pseudocolor images of Tony Blair that had been created by mapping different color scales onto the data values of the photograph. We studied several color scales that varied in the their luminance, hue, and saturation characteristics. The LAB gray scale was linear in L*, the HSV grayscale was roughly exponential in luminance and thus roughly linear in L*, and had a slightly greater dynamic range. The Heated Body color map had a compressive monotonicity in L*. To explore the role of luminance polarity, we studied two color maps that were linear in HSV saturation. In HSV, saturation is confounded with luminance. When the map is monotonically increasing in saturation, as defined in this space, it is monotonically decreasing in luminance; when the map is decreasing in saturation, it is increasing in luminance. To determine whether other variables could effectively represent the magnitude information in this image, we included two isoluminant color maps, one that was linear in hue (LAB Isoluminant Rainbow) and one that was linear in saturation (LAB Isoluminant Saturation). We also included the Rainbow color map that is the default color map in all commercial systems, and which is used ubiquitously in visualization.

For each color map, we constructed a family of seven subsets, each covering 25% of the color map’s range, and also mapped these onto the photographic image. This allowed us to compare color maps that all had a constant dynamic range (25% of the color scale). It also allowed us to study luminance and contrast effects more precisely, since each color map’s effect could be explored over a set of overlapping ranges.

In our experiments, we found that judgments of image naturalness, that is, the degree to which the color map accurately represented the intensity information in the image, depended on the luminance monotonicity of the color map. All color maps with a monotonic luminance component were rated favorably, including the two segments from the Rainbow color scale that increased monotonically in luminance. If the color map did not include a monotonic luminance component, however great the variation in hue or saturation, the image was not judged favorably. If the color map had a monotonic luminance component that was decreasing, the image was not judged favorably.

Perhaps the strongest result in these experiments is that for those color scales that included a monotonically increasing color component, the quality of the image increased logarithmically with the luminance contrast of the color scale. Those color scales for which the contrast of their monotonic luminance component exceeded 20% all produced at least 70% “good” ratings, suggesting a recommendation for color map selection.

5. Discussion

The results of these experiments suggest a method for visually evaluating color. In this method, the color scale of interest is mapped onto a photographic image of a face. If that image looks natural and recognizable, the user can infer that the color map has a monotonically-increasing luminance profile on the system where it is being viewed, making it a good candidate for representing continuous ordinal, and possibly interval data. Furthermore, the more natural and recognizable the image is, the higher the luminance contrast of that monotonic color scale, the better that scale should be in representing the magnitude information in those data.

We believe that the method we describe can be particularly useful in Internet environments where the color rendering properties of the client-side system is not known.

We envision that this method could be produced as a small applet or add-in to any visualization system, so that users could quickly select appropriate color maps from a library, or evaluate color maps they had constructed. We also envision packaging this applet with tools that let the user manipulate the color map interactively, while viewing the Which Blair image, in order to improve its performance on the fly.

6. Conclusion

In conclusion, we have proposed and validated, a quick perceptual method for identifying color scales with monotonically increasing luminance profiles. Since this method does not require display calibration or lengthy psychophysical procedures, we hope it will help lower the barrier to adopting perceptual color scales.

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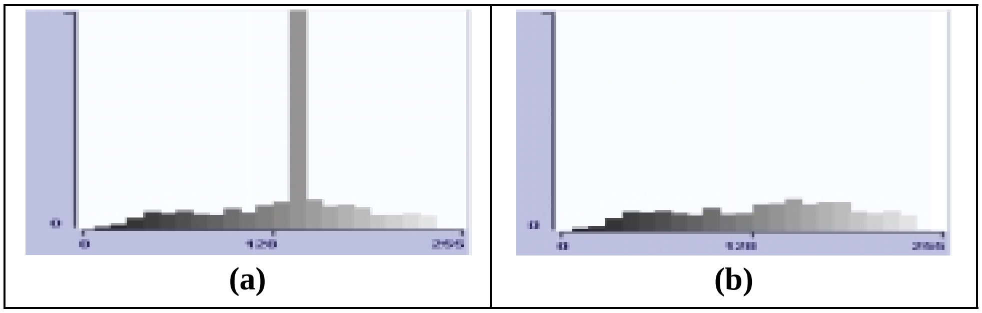
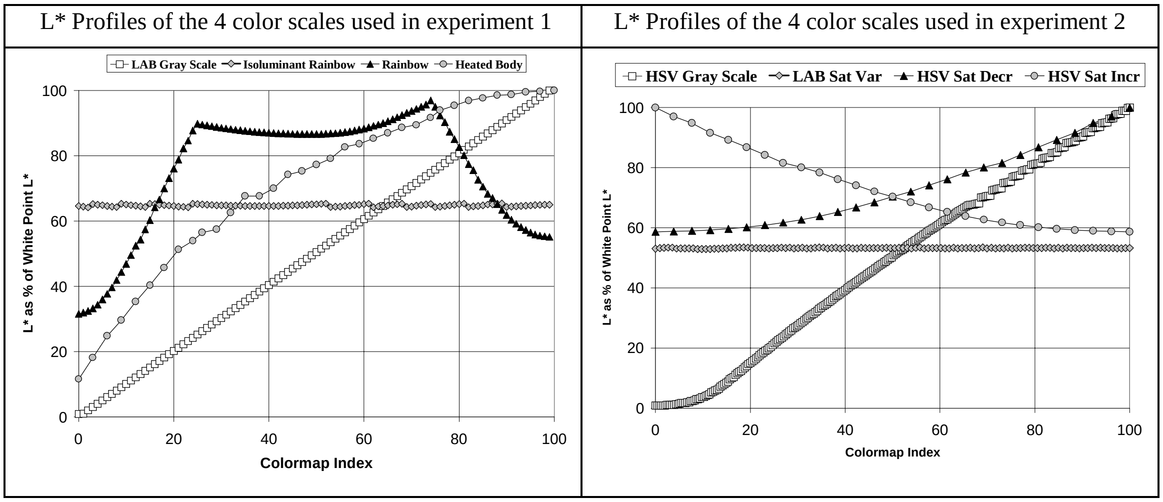


(a)

(b)

Figure 1: Histograms of pixel values of Tony Blair photograph (a) with and (b) without background values.


L* Profiles of the 4 color scales used in experiment 1

L* Profiles of the 4 color scales used in experiment 2

Figure 3: L* Profiles of the color scales used in experiments 1 (left) and 2 (right).

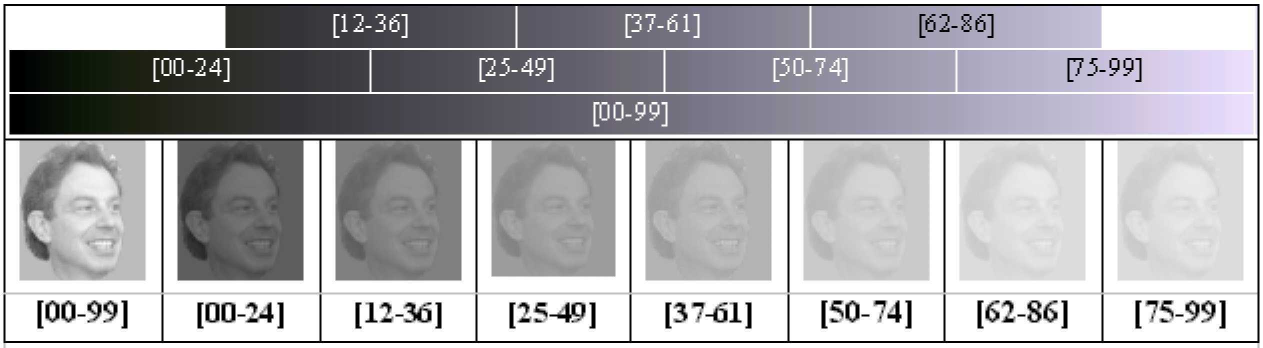


Figure 4: The 8 overlapping LAB grayscales (top), and the results of applying them to the Blair photograph (bottom).

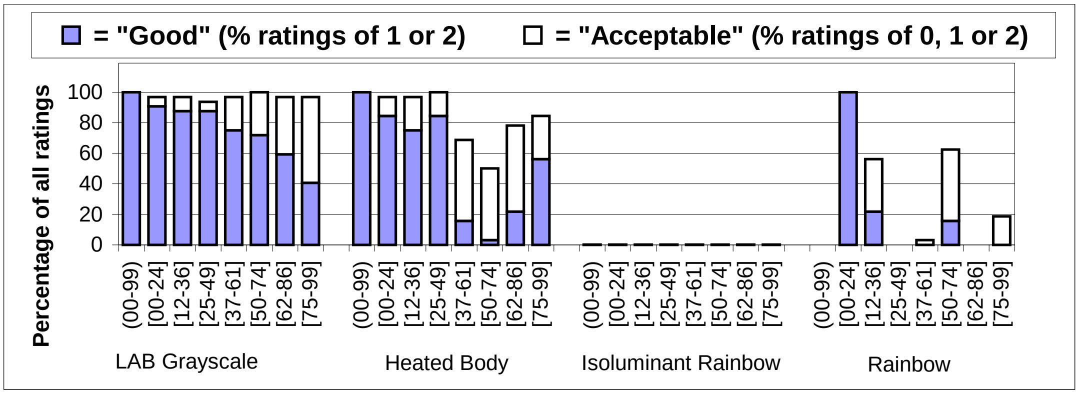


Figure 7 (a): Perceptual Ratings For The 4 Families Of Color Scales Tested In Experiment 1.

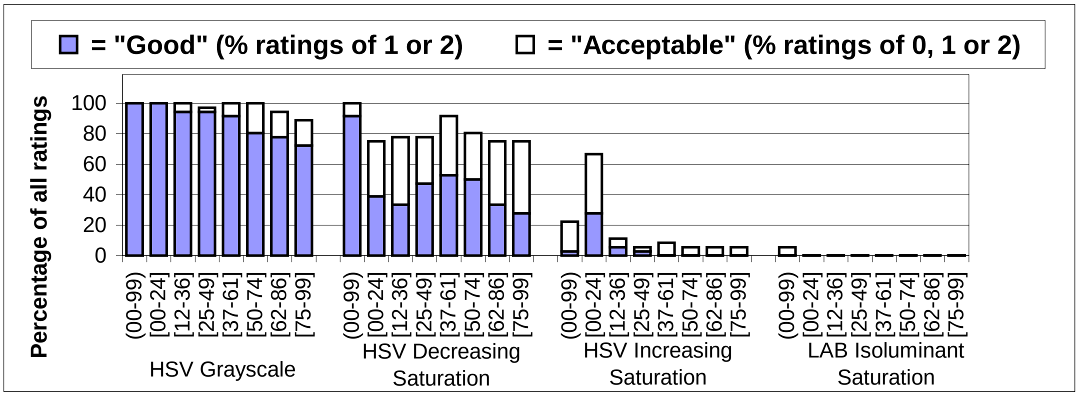


Figure 7 (b): Perceptual Ratings For The 4 Families Of Color Scales Tested In Experiment 2.

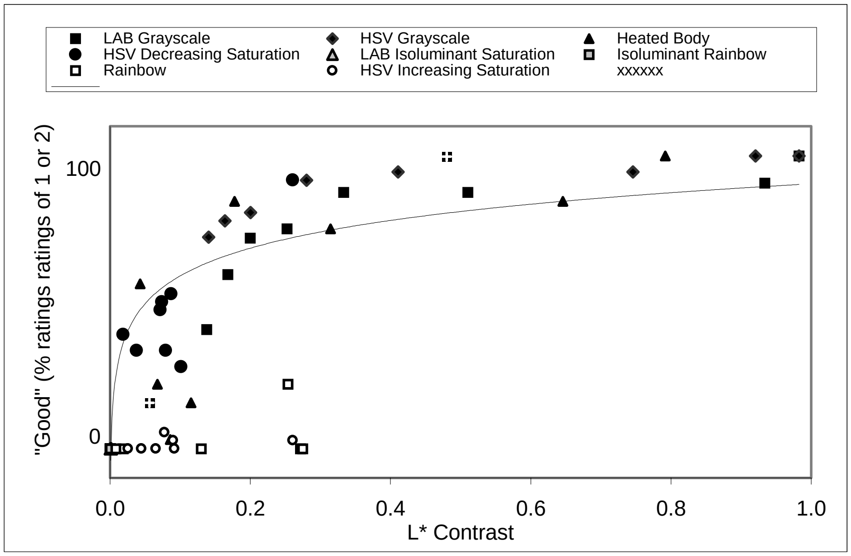


Figure 8: The relationship between L* contrast and percentage of favorable ratings. This relationship is logarithmic for color scales having monotonically increasing luminance.

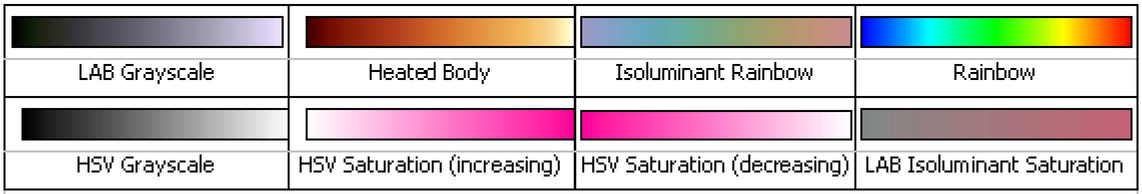


Figure2: The 8 color scales used in the Which Blair experiments

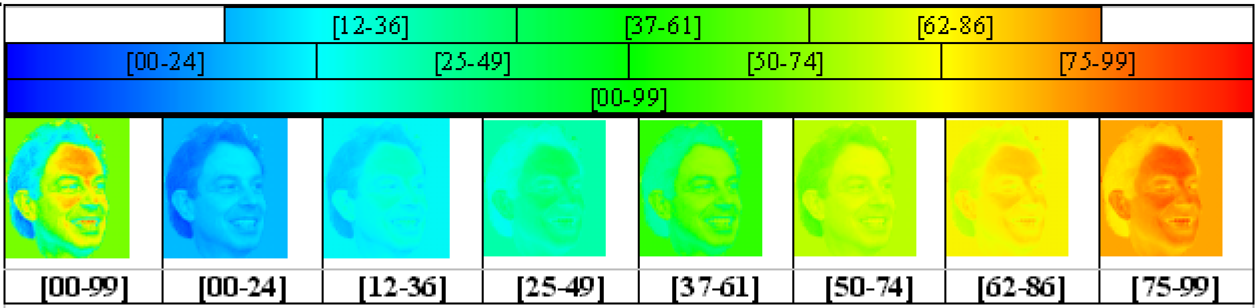


Figure 5 (a): The 8 overlapping Rainbow scales (top), applied to the Blair photograph (bottom).

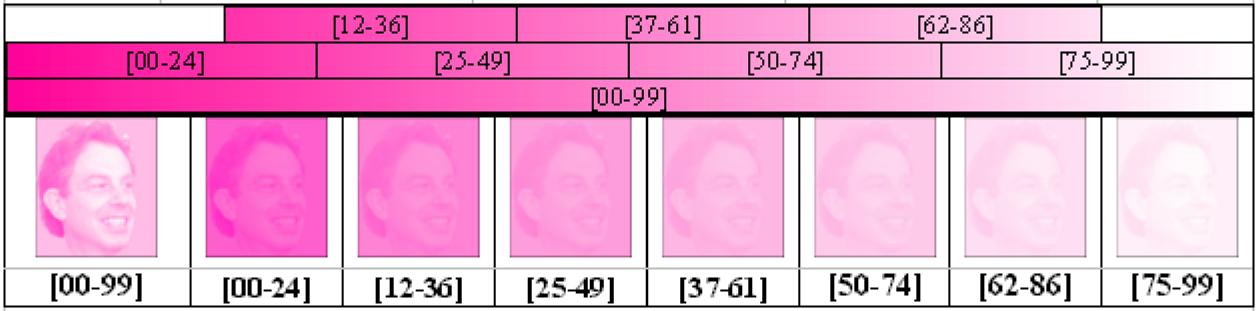


Figure 5 (b): The 8 overlapping HSV Decreasing Saturation scales (top), applied to the Blair photograph (bottom).

Figure 6: An example of the type of matrix of faces used in the Which Blair experiments.