Spatial Frequency and Lightness

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Abstract

A method of adjustment experiment was conducted in which observers matched the lightness of a test stimulus to the lightness of a reference stimulus. The reference stimulus and background were non-uniform and consisted of a blue noise pattern. The test stimulus and background were also non-uniform and consisted of a white noise pattern. In both cases, the background patterns were comprised of black and white pixels. The stimuli consisted of gray and either black or white pixels. Fourteen observers performed the experiment on a CRT in a dark surround. We found that there is an approximately 10 percent difference in the relative luminance for the matches between the white noise and blue noise conditions, and that this difference is statistically significant at a 95% confidence level. In this abstract, we discuss these non-equivalent backgrounds in relation with previous studies and also present some preliminary results for moving test stimuli.

Introduction

The perception of lightness has been described by Kuehni[1] as "the judgment of the brightness of a related color in relation to the average brightness of the surrounding colors". McCann[2] has reported results for a range of equivalent backgrounds "that despite a wide range of pattern types (snow, corners, side lines and asymmetry) the observer matches showed a high correlation with very simple spatial averages." Likewise, Fairchild[3] has also found "that traditional concepts of linear luminance integration and equivalent background are satisfactory on average".

In this paper, we report on a psychovisual experiment that tested if the perceived lightness of stimuli is indeed independent of the spatial frequency content of the background. The backgrounds have the same average luminance but consist of variegated noise that differs in spatial frequency properties. Specifically, white noise (or random texture with a broad and flat radially average power spectrum) is compared to blue noise (or a random texture that has been low pass filtered and consists primarily of higher frequencies). Ulichney[4] has noted "blue noise is visually pleasant because it does not clash with the structure of an image by adding one of its own or degrade it by being too 'noisy' or uncorrelated". The primary motivation of this work is a curiosity regarding the perception of complex stimuli and not necessarily the derivation or refining of a specific model of the human visual system.

There are a number of inter-related topics to be considered with respect to this paper. For instance, research in the areas of contrast sensitivity, noise perception, halftoning techniques, color appearance, edge perception, masking, simultaneous contrast, assimilation and other topics are related to the results presented in this abstract. There is an extensive literature[5] on contrast sensitivity but as Yu et al.[6] note this phenomenon is "most often studied with sinusoidal gratings". There is also some data to support the hypothesis[7] that "at suprathreshold contrasts the human visual system approximates scale-invariance rather well, better than might be expected from visual performance at contrast threshold." For the stimuli used in this experiment noise perception[8,9] is a relevant topic but often this topic is focused on white or random noise. Research on blue noise is typically focused on halftoning and the resulting texture. Wang et al.[10] report recent results for blue noise and a fifty-fifty checkerboard and they note "little research has been reported to study supra-threshold human perception of lightness differences under high frequencies."

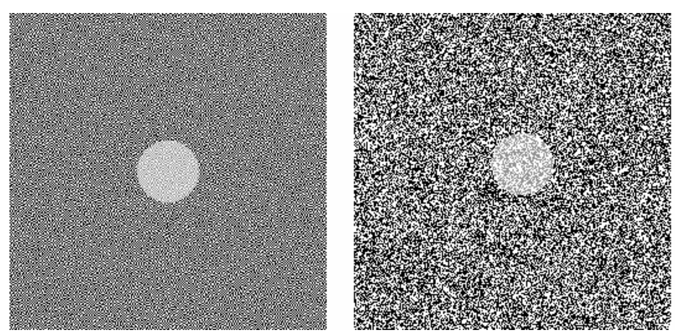

Figure 1. Reference background and stimuli on the left and test background and stimuli on the right. The background consists of black and white pixels in both cases. The central stimulus consists of a middle gray, 128 out of 255 digital counts, and white pixels

Experimental Set-up

The background and stimuli were created to have either white or blue noise properties. The white noise background was created using a random number generator while the blue noise background was created using error diffusion. The background consisted of 50 percent white and 50 percent black pixels in both cases and had an average luminance of 33 cd/m2. The stimuli were created by selectively adding a constant gray to a central disk. In one case, this gray value replaced the white pixels and in the other case the black pixels. An example of the backgrounds and stimuli used in this experiment are shown in Figure 1. Note that both the backgrounds and the stimuli are non-uniform and that the average luminance for the backgrounds and the stimuli is equal. These backgrounds and stimuli were viewed on a SONY Multiscan 500 PS CRT in a darkened room. The backgrounds were shown at the native resolution of the display and had dimensions of 256 by 256 pixels. The stimuli were viewed at a distance of approximately 45 centimeters and the resulting size of the stimulus was about 2 degrees. The display had a white point of D65, EOCF of about 2.2 and maximum luminance of 70 cd/m^2. The backgrounds and stimuli were then shown side-by-side.

The observers were instructed as follows: “Please use the 'lighter' and 'darker' buttons to match the lightness of the stimulus on the right to the stimulus on the left. The objective is to match the overall lightness of stimuli. When you are satisfied with the match press the "Next" button to get the next stimuli. Please use a normal viewing distance, such as whatever distance you typically use when reading email, and do not de-focus, squint, back up from your display or otherwise blur the stimuli.”

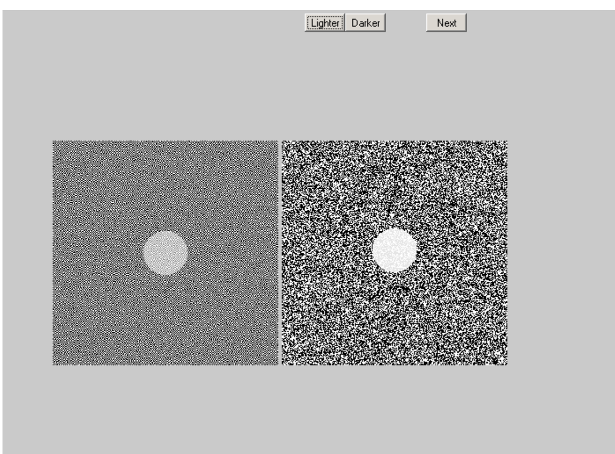

Figure 2. Screen shot of the experimental layout. The reference background and stimuli are shown on the left while the test background and stimuli are shown on the right. The light and darker buttons modified the lightness of the gray of the stimuli.

An example screen for the experiment is shown in Figure 2. This figure shows the ‘lighter’ and ‘darker’ buttons made available for the observers to adjust the test stimulus. The lightness of the gray of the test stimuli was randomized for each observer and each trial. The remainder of the screen outside of the two backgrounds was filled with a uniform gray with a luminance of 48 cd/m^2. There were four test stimuli: two fixed and two moving. The moving test stimuli followed a fixed vertical bouncing motion subtending roughly 6 degrees at a rate of one complete top to bottom bounce in roughly two seconds. The first reference stimulus consisted of a gray and black blue noise pattern and had an average luminance of 20.9 cd/m^2. The second reference stimulus consisted of a gray and white blue noise pattern and had an average luminance of 46.6 cd/m^2. The results for the moving stimuli will be considered briefly in the discussion section. The experiment was implemented as a JAVA program. A total of 14 observers participated in the laboratory version of the experiment. The four experimental conditions are also listed in tabular form in Table 1 of the results and discussion section for reference.

Figure 3 illustrates the two-dimensional power spectrum of the backgrounds. The absolute values of the magnitudes were computed using Matlab fft2 and are shown as centered and re-scaled images. More energy is illustrated by whiter and less energy by darker areas. The lack of low frequency components for the blue noise background is evident in the dark area near the center. In comparison the white noise power spectrum consists of the full range of frequencies.

Table 1. Summary of Experimental Results for Frequency and Lightness Experiment.

Exp. Phase	Reference stimulus	Reference stimulus mean Y (cd/m^2)	Test stimulus	Mean match test Y (cd/m^2)	Two standard errors (cd/m^2)
1	Grey-black blue noise pattern	20.9	White noise	16.2	1.7
2	Gray-black blue noise pattern	20.9	Moving white noise	18.2	1.9
3	Gray-white blue noise pattern	46.6	White noise	51.3	2.1
4	Gray-white blue noise pattern	46.6	Moving white noise	48.3	2.8

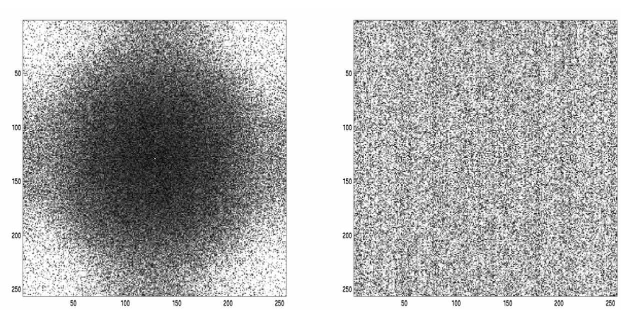

Figure 3. The two-dimensional power spectra for the two experimental backgrounds used in the experiment. The blue noise background is shown on the left and the white noise background is shown on the right.

Results

The overall results are shown in tabular form in Table 1. Note that the mean stimulus luminance was 20.9 cd/m2 for phases 1 and 2 and 46.6 cd/m2 for phases 3 and 4. The phases were randomized for each observer, but in all cases the blue noise background was the reference background and the white noise background was the test background. The results are also shown graphically in Figures 4 and 5. These figures have the different phases on the x-axis and the mean luminance in cd/m^2 on the y-axis. Error bars are shown as plus or minus two standard errors.

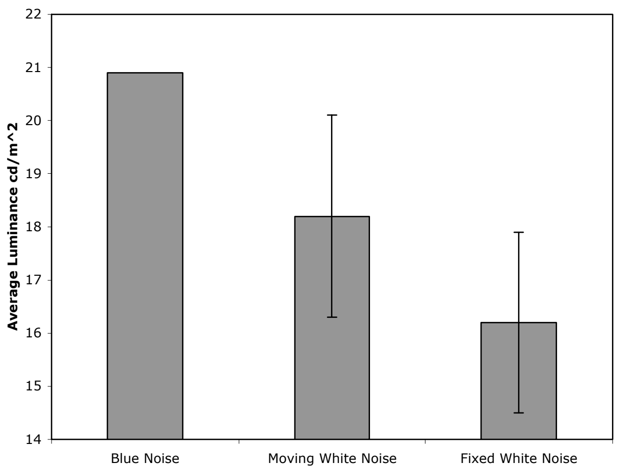

Figure 4. Results from phases 1 and 2 of the experiment.

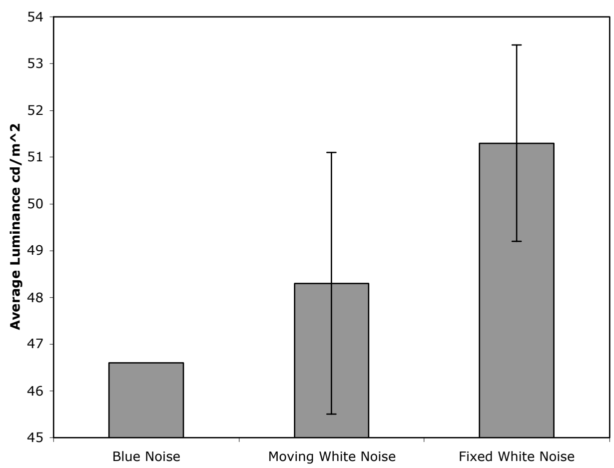

Figure 5. Results from phases 4 and 5 of the experiment.

The results in Figures 4 and 5 show the reference stimulus luminance farthest to the left. This is for reference purposes and can be compared to the two neighboring bars with error bars. The results for the fixed or static test stimuli with white noise pattern are shown farthest to the right. The results for the moving test stimuli are shown in the middle. In both cases, the average matching luminance for the fixed test stimuli was statistically significantly different than the mean reference stimulus luminance. For phase 1, the test stimulus had to have the luminance lowered by over 20 percent to match the reference stimulus. For phase 3, the test stimulus had to have the luminance raised by 10 percent to match the reference stimulus. The results for the moving test stimuli were intermediate to the reference and the fixed test stimuli. The error bars are not narrow enough to support statistical significance at the 95% confidence limit, although there is a definite trend worth to additionally investigate. Participants made specific comments about the difficulty of matching the moving test stimulus to the reference stimulus. In addition, the authors noted a slight difference in the lightness of the moving test stimulus if the stimulus was moving at a constant speed or changing direction.

Discussion

The results of this experiment demonstrate a specific instance of non-equivalent backgrounds. That is, backgrounds whose mean luminances are the same, but whose corresponding luminances for matching stimuli differ. However, these backgrounds must also be matched with corresponding stimuli such that a blue noise background and stimuli will yield stimulus mismatches relative to a white noise background and stimulus. The cause of these mismatches is interesting to consider, but first it is informative to make some qualitative observations regarding the two backgrounds and stimuli.

Consider blue and white noise backgrounds and stimuli where the stimuli have equal luminances. In this case, the blue noise stimulus is much more evident or has more distinct “edges” between the stimuli and background, as compared to the white stimulus and background. However, the white noise stimulus can be made more visible by either defocusing the eye by squinting, by shifting the white noise stimulus to the peripheral vision or by backing up to a greater distance from the white noise stimulus. In all three of these cases, the highest frequency information is reduced. As a result, more low frequency information is used by the visual system and the white noise stimulus is more visible. In a similar manner, adding motion to the white noise stimulus creates a temporal edge that allows the white noise stimulus to be more visible.

However, we found that there is an approximately 10 percent difference in the relative luminance for the matches between the white noise and blue noise conditions, and that this difference is statistically significant at a 95% confidence level. Thus, the spatial frequency content of the background can in some cases influence lightness perception, and could be considered in future prediction models. Color or image appearance models such as CIECAM02[11] or iCAM,[12] often use a spatially averaged background or surround. Likewise, initial testing with one version[13] of the Retinex algorithm predicted minimal differences for the experimental conditions described in this paper. It will be informative to test alternate models, such as two-dimensional difference-of-Gaussian filtering,[14] with respect to these results.

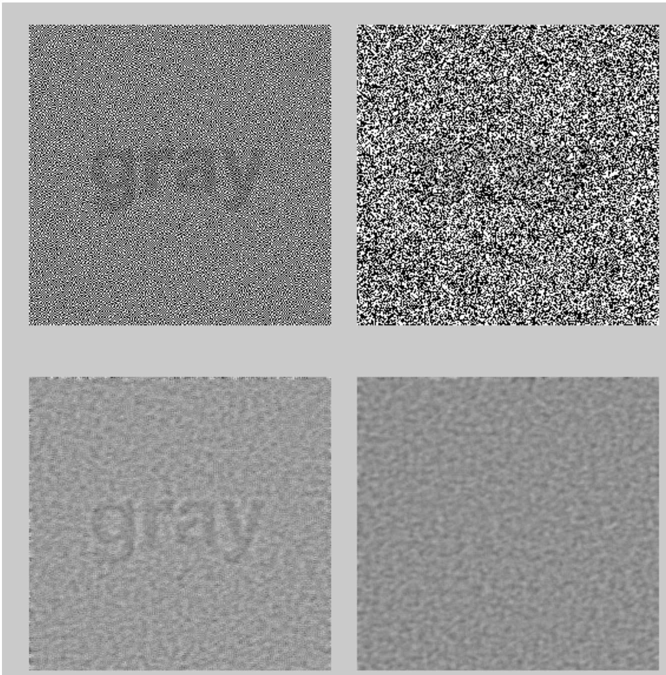

Figure 6. Matched backgrounds and text "gray" with blue noise, shown left, and white noise textures, shown right. The bottom shows the above images filtered by a difference of Gaussians.

These results could be interpreted as an example of visual stimuli that differentially stimulate the spatial frequency channels of the human visual system. Frequency adaptation is frequently cited as a visual phenomenon supporting multi-channel human visual models. From the perspective of multi-channel vision, the blue noise pattern provides a greater difference between channels relative to a white noise pattern, especially in comparison to a simple low pass average. To illustrate a difference of Gaussians is computed for the word "gray" as an example in Figure 6.

Conclusions

There are statistically significant non-equivalent backgrounds where a simple spatial average is not sufficient to characterize the resulting stimulus luminance. These backgrounds differ based on the spatial frequency properties. Specifically, it can be shown that white noise stimuli must be over 10 percent lighter or darker than the corresponding blue noise stimuli in order to achieve a lightness match. The results are statistically significant at the 95 percent confidence level and were derived using a method of adjustment experiment with 14 observers. Moving the white noise stimuli appears to yield a closer match to the blue noise reference stimuli but additional testing is required to characterize this effect. It can also be seen that these white noise stimuli can be made more visible by defocusing the eye by squinting, shifting the stimulus to the periphery or by increasing the viewing distance significantly. It is interesting to consider these results and effects with respect to multi-channel visual models.

References

1. Rolf G. Kuehni, Color: Essence and Logic, Van Nostrand Reinhold, New York, NY, p. 41 (1993).
2. John J. McCann and Alessandro Rizzi, "The Spatial Properties of Contrast", Proc. IS&T/SID 11th Color Imaging Conference, 51-58 (2003).
3. Mark D. Fairchild, "A Victory for Equivalent Background – On Average", Proc. IS&T/SID 7th Color Imaging Conference, 87-92 (1999).
4. Robert Ulichney, Digital Halftoning, MIT Press, Cambridge, MA, p. 338 (1993).
5. Peter G. Barten, Contrast Sensitivity of the Human Eye and its Effect on Image Quality, SPIE Optical Engineering Press, Bellingham, WA (1999).
6. Cong Yu, Stanley A. Klein, and Dennis M. Levi, "Surround modulation of perceived contrast and the role of brightness induction", Journal of Vision, 1(1), 18-31 (2001).
7. J.H.T. Jamar and J.J. Koenderick, "Sine-Wave Gratings: Scale Invariance and Spatial Integration at Suprathreshold Contrast", Vision Res. 23(8), 805-10 (1983).
8. Roger P. Dooley and Rodney Shaw, "Noise perception in electrophotography", J. Appl. Photogr. Eng. 5(4), 190-196 (1979).
9. A. van Meeteren and J. M. Valeton, "Effects of pictorial noise interfering with visual detection", J. Opt. Soc. Am. A, 5(3), 438-444 (1988).
10. Muge Wang, Kevin J. Parker, Kevin Spaulding, Qing Yu, Rodney Miller, "Optimal output level selection for multilevel halftoning using spatial modulated gratings", J. Img. Sci. Tech. 47(4), 309-326 (2003)
11. Comission Internationale de Eclairage, A Colour Appearance Model for Colour Management Systems: CIECAM02, Publication 159 (2004).
12. Mark D. Fairchild and Garrett M. Johnson, "iCAM, framework for image appearance, differences and quality", J. Elect. Img. 13(1), 126-138 (2004)
13. Brian Funt, Florian Ciurea and John McCann, "Retinex in Matlab™" J. Elect. Img. 13(1), 48-57 (2004).
14. Barabara Blakeslee and Mark McCourt, "A multiscale spatial filtering account of the Wertheimer-Benary effect and the corrugated Mondrian", Vision Res., 41, 2487-2502 (2001).

Biography

Nathan Moroney is a senior color researcher at Hewlett-Packard Laboratories. Previously, he worked for the Barcelona division of Hewlett-Packard and the RIT Research Corporation. He has a Master degree in Color Science for the Munsell Color Science Laboratory and a Bachelors degree in Color Science for the Philadelphia University.