The Appearance of Brightness and Lightness

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Abstract

In simplest terms, *brightness* is the appearance of luminance and *lightness* is the appearance of objects. The experiments in this paper measure the appearance of three visible faces of a real cube in real-life illumination. Three faces of the cube are painted white and the other three are painted different shades of gray. When the observer sees three white faces the experiment measures the appearance of illumination. When the experimenter rotates the cube to make visible a face with a different reflectance in the same illumination, then the experiment measures the appearance of objects.

The results of matching experiments show that humans make the same match for luminance changes caused by illumination as those caused by reflectance. Humans can successfully recognize changes in whites due to illumination. They mistakenly interpret reflectance changes as illuminant position changes. However, in the same image they make the same matches for dark areas that were caused by illumination, reflectance or both.

Introduction

For more than two centuries, the study of vision has generated a multiplicity of intellectual frameworks to describe appearance. In 1765 Bishop Thomas Reid expressed the philosophical need for the distinction between sensation and perception[1]. Helmholtz[2] described that humans have the ability to discount the illuminant, so as to see the surfaces of objects rather than the quanta catch of the receptors. Katz[3] specified 11 modes of visual perception. Evans combined these into three general modes, namely aperture (film) mode, object (surface) mode and illumination mode.[4] Hering introduced the idea of a duality of achromatic stimuli.[5] For him quality, or lightness, is function of the ratio of the white and black components, regardless of magnitude. Weight, or brightness, is a function of absolute magnitudes.[6] Since Hering there have been many different definitions of lightness and brightness.

These intellectual frameworks all arise from three very important visual observations. First, the appearance of light falling on a patch of retina changes when the stimulus around that patch changes. Second, since its inception, psychophysics has regarded as its foundation the concept of describing human responses as a mathematical functions of stimulus. Weber's Law, Ricco's Law, Piper's Law, Steven's Power Law are all examples.[7] The sense of vision is responsive to light, so visual response, or appearance can be described as a function of radiance, or better, luminance using one of many human spectral sensitivity functions. The second important observation, disturbing to traditional psychophysics, is that the slope of psychometric function for appearance vs. luminance varies with the spatial properties of the stimulus. Some stimulus configurations cause a slow, low-slope change of appearance with luminance. Overall change of global illumination is a good example. Other configurations demonstrate rapid, high-slope change of appearance with luminance. Varying the luminance of a test patch surrounded by a higher luminance background is a good example. The third observation is that the response of the observer varies with the question presented. In real scenes, we get different matching data from asking the observer to "match the perceived surface of an object" and from asking "how light or dark does an area appears". These three properties are responsible for many intertwined philosophical, psychophysical, physical constructs incorporated in our understanding of human vision.

Sensation vs. Perception

Sensation is used to describe the early sensory response of receptors. It is created by low-level mechanisms. Perception implies cognition. It "includes the combination of different sensation and the utilization of past experience to recognize objects"[8]. In *lightness* and *brightness* experiments we have to separate the task of matching a gray appearance from the task of recognizing the surface of the object. Too often today's common usage ignores this distinction, even though experiments have shown that gray-level sensation matches produce different results than object recognition perception matches.[9,10] Too often we are faced with conflicting lightness and brightness experimental data that are in fact caused by asking observers different questions using the same terminology.

Observers for these experiments were shown the example of the raft on the lake in sun and shade[9]. This picture was used to illustrate that the two faces of the raft have different sensations - one is lighter, while the other is darker and bluer. In contrast, the two faces of the raft have the same perception - both the side in the sun and the side in shade are recognized to have the same painted surface. In the following experiments, observers were asked to match sensations, and not to infer the reflectances of the paint by discounting the illumination. They were asked to think of the Standard Lightness Display as paints on an artist's palette. If they were a fine-arts painter, which paint would they select to reproduce the appearance of the cube faces in a painting.

Figure 1 shows a photograph of the corner of the room discussed in the text. The left wall is whiter than the back, and both are whiter than the top wall. Are these differences in apperances differences in lightness or brightness? Which psychometric function describes the appearance of these walls?

Brightness vs. Lightness

Brightness has been defined as both a sensation [7,8] and as a perception.[11] Common to all definitions is the idea that it is apparent luminance. Katz's brightness is apparent illumination of a surface[3]. Our everday experience is that there are small changes in brightness with large changes in luminance. Lightness has also been defined as a sensation,[7,9] and as a perception,[8,11] Common to all definitions is the idea lightness is relative to white areas in the field of view. Often lightness is associated with the local interplay of reflectances of objects, or relative brightnesses normalized for changes in illumination.[12]

Hunt, Nayatani and Fairchild

The CIE has recently recognized the pioneering work by Hunt along with that of Nayatani and Fairchild by establishing a Color Appearance Model as an international standard. The model incorporates many different sets of visual experiments into a single set of equations describing lightness, brightness, colorfulness, chroma and hue angle. Fairchild's book "*Color Appearance Models*" describes the details of work in Hunt's, Nayatani's and Fairchild's laboratories and the integration of all three approaches into a single standard.[12] In a review of the book I expressed the desire for more details about calculating CIECAM values from image data found in real life scenes.[13] (This kind of extension of the model is being studied currently by a CIE subcommittee.[13)] The review discussed the appearance of a corner of a room. In Figure 1 we see three intersecting walls. The illumination is coming from the right. The left wall has the highest luminance, the back wall has less and the top slanted wall has the least luminance. These walls have different achromatic appearances. Hunt explained in a letter to Color Research and Applications[14] that CIECAM97 used measurements of both the luminance from the scene and the luminance from a white reference at each pixel to calculate lightness and brightness. In the corner of the room, the CIECAM97 lightnesses were all identical because this calculation normalized the scene luminance by the white reference luminance. The model describes the walls' differences in appearance by the differences in brightness. This discussion led to the present experiment.[15] CIECAM97 predicts that the appearance of the walls will track their brightness function when the illumination varies. Further, it will track lightness function as their reflectance varies. By varying the illuminants and repainting the walls we can test whether human vision uses different functions in real life scenes.

There are alternative definitions we can apply to this scene. The three walls are all seen relative to each other, so that some definitions would describe the differences in appearance as lightness. The idea that came out of the discussions with Hunt is seen in the present experiments. Namely, can we test whether the rate of change of appearance vs. luminance is a unique signature of the lightness/ brightness construct?

The literature[7] is rich with experiments measuring the changes of *lightness* as a function of local luminance and *brightness* as a function of global luminance. However, there is very little research on the appearance of *lightness* and *brightness* in the same real scene. Can we apply the rules we have learned by experiment on local *lightness* and global *brightness* to scenes that contain local variations in both reflectances and illuminations?

Experiment

We asked observers to match the sensations generated by the three visible faces of a cube in real-life illumination. Figure 2 describes the physical set up of the scene. Several observers made matches by comparing the appearance of the cube faces to a Standard Lightness Display.[16]

Observers were read the following instructions: "You are a fine arts painter. You are about to paint a canvas of the cube in front of you on the right. Your pallet of paints is on the left. Identify your paint selection [numbers between 1 and 20] to render the left, top, and right faces of the cube." Observers were asked to close their eyes as the experimenter rotated the cube to a new orientation. The position of the cube

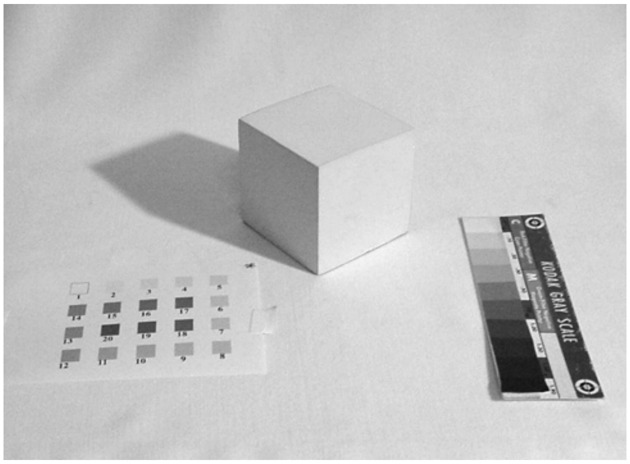


Figure 2 shows the experiment. This picture was taken from the eyepoint of the observer. The experimenter placed the 3-inch, painted wooden cube at a distance of 2 feet from the observer on a piece of white velvet on a desk. The front, vertical edge of the cube subtended 7 degrees. There were two lights on in the room. One was a ceiling lamp with a glass diffuser used to illuminate the room. The second was a reflector photoflood lamp placed behind and above the observers and over their right shoulder. The photoflood was aimed at the cube. The photoflood dominated the illumination falling on the right face of the cube, as well as the top face. The shadow cast by the cube indicates the position of the photoflood. The ceiling light controlled the illumination of the left face of the cube. The left-front of the picture shows the "Standard Lightness Display" used by observers to match the appearance of the cube faces. The right shows a calibrated gray scale with known reflectances. This reflectance standard was photographed with the cube and "Standard Lightness Display" as means of calibrating the actual radiances in the scene. The experimenter removed the reflectance standard from the field of view while making psychophysical measurements. In this image all three faces of the cube are white. As the experimenter rotated the cube, the three gray faces of the cube were visible, in turn.

was marked on the table so the experimenter could repeatably reposition the cube in the same place so as to have the same illumination.

The radiances from the scene were calibrated with both a hand held photometer, and a digital camera. Calibrations were made using digital image data and known reflectance standards. Three white faces of the cube allow us to measure the appearance changes caused by illumination with constant reflectance. As well, the three gray faces (W= 1.00, G1= 0.78, G2= 0.51, G3=0.44) allow the measurement of changes due to reflectance in constant illumination. The remaining combinations measure the effect of combined reflectance and illumination. If we rotate the cube so that we see all possible combinations of orientation sequentially, we have 24 different measurements for each of the three faces, or 72 measurements. Several observers were asked to make these matches on static displays, indoors, using incadescent illumination.

The question tested in this experiment is whether illumination changes cause different matches than reflectance changes.

Results for White Surround

The experimental matches for one observer are plotted in Figures 3. Figure 3 (left) shows the average data from all matches using the three white reflectances. It plots the effect of changing the illumination, while holding reflectance constant. The solid line is drawn at slope 1.0.

Figure 3 (right) shows the average data from all matches using the four different reflectances in constant illumination. The three symbols identify the separate data from left (low illumination), middle/top (middle illumination) and right (high illumination). The solid line is also drawn at slope 1.0. If illumination varied at a lower slope than reflectances the data should diverge. They do not.

This experiment fails to find different matches due to changes in illumination vs. reflectance. The data in these graphs show indistinguishable changes in sensation with luminance. This implies that, for a complex image, spatial relationships are more important than illumination or reflectance.

Results for Black Surround

In analyzing the results of this experiment it became obvious that a significant source of data spread was the fact that the luminance measured from cube faces near the white velvet cloth was higher than those made near the top of the cube. Reflected light from the cloth increased the variability of the luminance measurements across the face of the cube. The data plotted in Figure 3 was average radiance across the entire face of the cube. In the next experiment we introduced a piece of black velvet under the cube. It reduced the variability of luminance across the face of the cube.

Figures 4 and 5 shows the experimental matches for two observers using a black velvet cloth under the cube. Figure 4 (left) shows a photograph of the scene with high-contrast, right-side illumination. Figure 4 (right) plots the matches for luminances changed by both illumination and the reflectance. Figure 5 (left) shows a photograph of the scene with moderate-contrast, left-side illumination. Figure 5 (right) plots the matches.

The data in Figures 4 and 5 shows that observers fail to differentiate changes in appearance caused by illumination and reflectance. The data in these graphs show indistinguishable changes in sensation with luminance. As seen from the data in Figure 3, this implies that, for complex images, the important distinction is a result of spatial properties, rather than illumination and reflectance. Figures 3, 4 and 5 include a slope 1.0 line as an indication of where the data would fall if the observer chose to match luminances. The results in Figure 3 with a white cloth under the cube fall close to the slope 1.0 line. The data from Figures 4 and 5 fall significantly above the line. The surrounding black cloth shows a significant effect on the average matching chip, but illumination and reflectance do not. Vision uses spatial comparisons for this fine art painter task, and is indifferent to whether the array of luminances was caused by reflectance or illumination.

Discussion

This paper reports experiments asking the observer to report the appearance of achromatic stimuli. It does this by asking

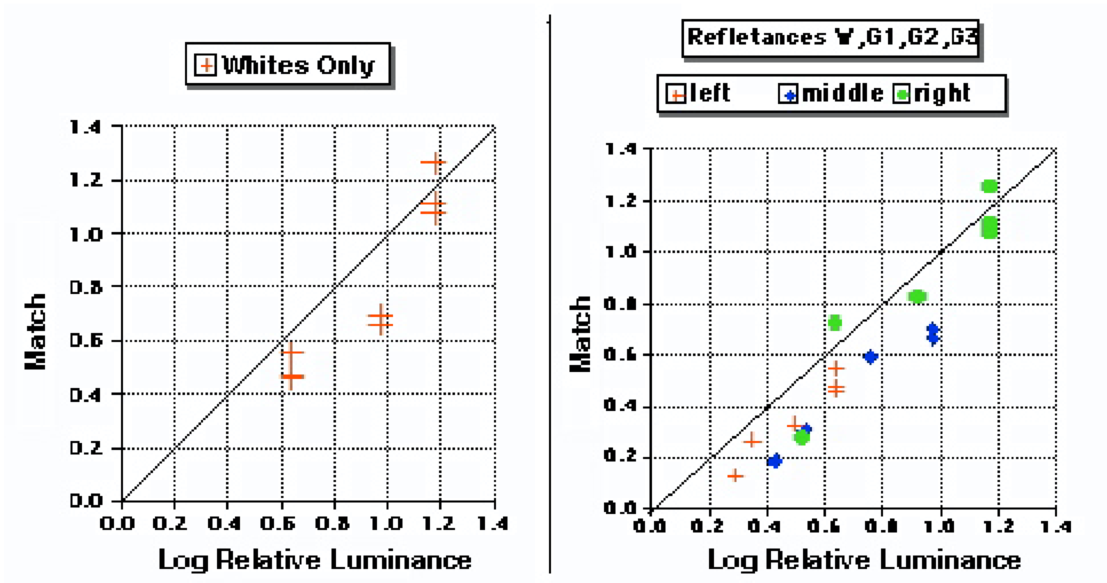


Figure 3 (left) shows the appearance of cube faces using only white reflectances. This experiment measures brightness. The horizontal axis plots the log relative luminances from the white faces. The vertical axis plots matching log relative luminances from the Standard Lightness Display shown on the left of Figure 2. The data falls close to, but slightly below, the slope 1.0 line. Figure 3(right) shows the appearance of cube faces using both white and gray reflectances. The horizontal axis plots the log relative luminances from the faces. The vertical axis plots matching log relative luminances. The data from the left, middle/top and right faces are plotted with different symbols. As in Figure 3(left), the data falls close to the slope 1.0 line. Observers make the same matches for darker areas that were caused by illumination, reflectance or both.

the observer to do a specific task. It attempts to avoid asking the observer to understand terminology such as lightness, brightness, sensation, and perception. If experts in the field do not use them consistently, why should observers? The experiment's goal is to test whether actual illuminations and reflectances influence the observers matching task.

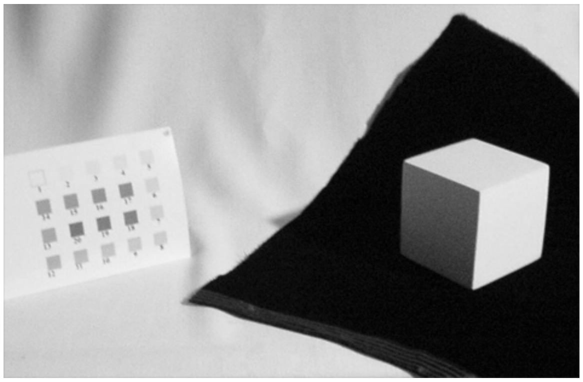
Many experiments [17] have reported that both large and small single patches of light on the retina generate low-slope psychometric functions. That is, appearance changes slowly as a function of luminance. With more complex images, with a test field and a surround, the maxima change as a slow function of luminance, while areas darker than the maxima exhibit a much more rapid rate of change, (i.e., Bodman et. al. for data). In unpublished experiments we have observed that in complex images, the maxima in the field of view follow this same low-slope function, while patches of light darker than the local maxima exhibit high-slope changes in appearance with luminance.

So far in this discussion we have avoided all the terminology, and more important, all the intellectual constructs or frameworks described in the introduction. This raises the question about how useful are these conflicting notions in explaining what we see. Fortunately, we can use the well defined physical constructs of reflectance and illumination to test whether they are important to observers. They are not. We can take them off the list. Perhaps, in the future we can come to understand that aperture colors are just the result of single patches of light on the retina and that object colors are the result of high-slope visual responses to radiances below the maxima. Color constancy is the result of independent application of these achromatic observations to each receptor type, rods, L, M, and S cones.[18] Experiments, such as Whites effect[19], Benary's Cross[20] and Adelson's Diamond Walls[21], seem to require top-down perceptual influence on appearance. On more careful scrutiny, it turns out they are explained by low-spatial frequency channel sampling.[22] Asking observers to guess an object's surface is an entirely different question from appearance matching and should have an entirely independent computational model.

The results of this experiment clearly show that reflectance and illumination are not important to the visual system for performing the fine art painter matching task. How many other constructs created by visual observations can be understood in terms of spatial interactions? How many 19th century constructs will survive our 21st century understanding of human spatial image processing?

How are these cubes perceived?

As described earlier, we can ask the observers the perception question. What can you tell us about the cube as an object? When shown the three white faces of the cube, they report that the cube has uniform reflectance and that the light is coming from a direction consistent with its actual position. When presented with different reflectance faces in different orientations, they also report that the cube is uniform in reflectance, and now the illuminant in a new, incorrect loca-



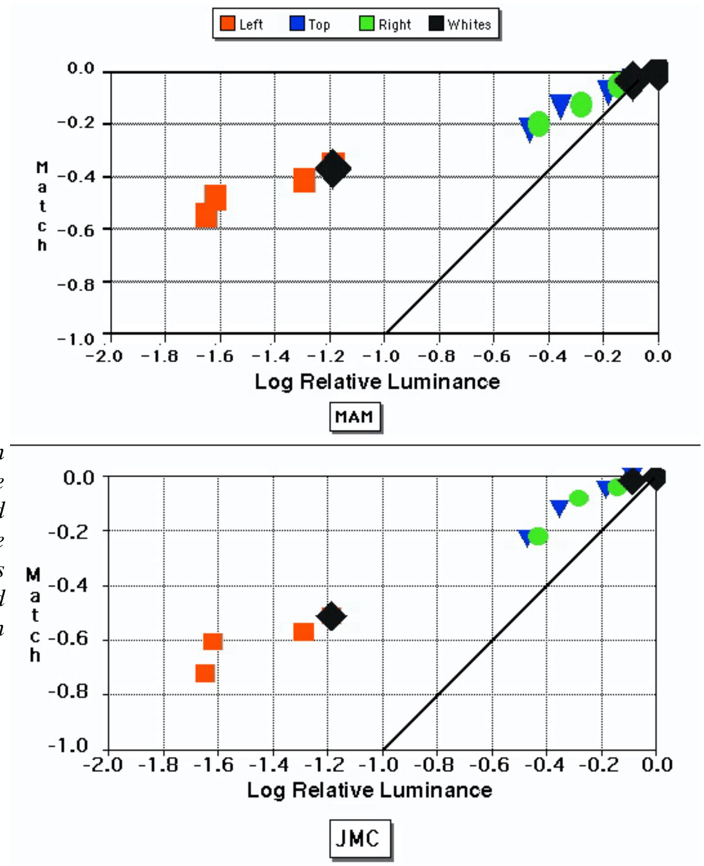
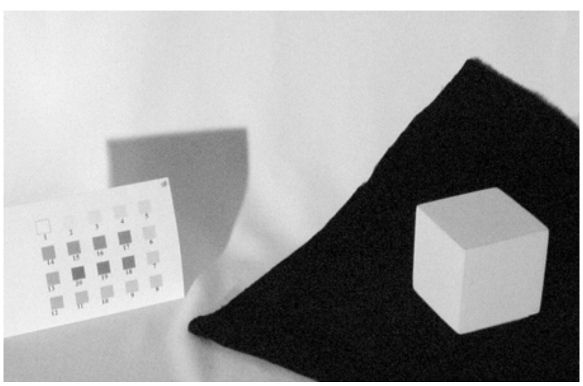


Figure 4 shows a photograph (above) of the right illumination experiment. The matching data for two observers is shown on the right. The horizontal axis plots log relative luminance measured from the eyepoint of the observer. The vertical axis plots log relative luminance of the matching square on the left. The squares, triangles and circles plot data from different reflectances in the left, top, and right positions. The larger diamonds plot the data from illumination only matches for all white reflectances.



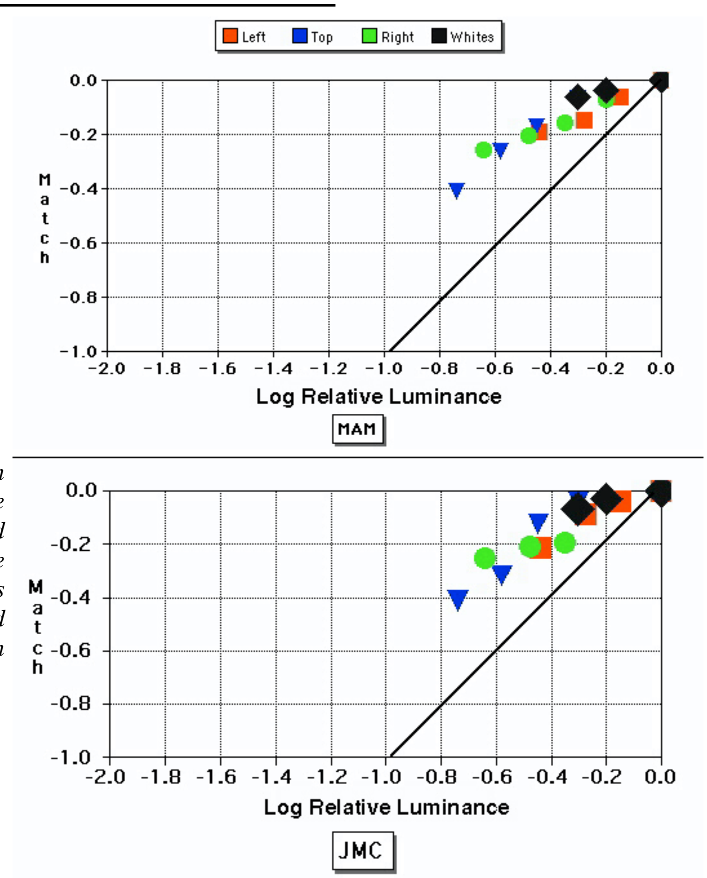


Figure 5 shows a photograph (above) of the left illumination experiment. The matching data for two observers is shown on the right. The horizontal axis plots log relative luminance measured from the eyepoint of the observer. The vertical axis plots log relative luminance of the matching square on the left. The squares, triangles and circles plot data from different reflectances in the left, top, and right positions. The larger diamonds plot the data from illumination only matches for all white reflectances.

tion. The perception of this painted cube stimulates new illuminant positions, not new surface colors. This is true despite the fact that the cast shadow of the cube provides information about the actual position of the illuminant. The shadow does not have a large effect on the observer's perception.[23]

Summary

These experiments measured the change in appearance of cube faces as influenced by illumination, reflectance and both. The experiments looked for different slopes for illumination and reflectance. We found that observers did not differentiate between the different causes of luminance reduction. Both illumination and reflectance change appearance at the same rate.

It is the spatial properties of the stimulus that cause the variable rates of change with luminance, not their intellectual constructs and frameworks.

Acknowledgements

I wish to thank Bob Hunt and Mary McCann for their helpful discussions.

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