Perception, 2006, volume 35, pages 291 – 301

DOI:10.1068/p5461

Testing the coplanar ratio hypothesis of lightness perception

Piers D L Howe
Harvard Medical School, 220 Longwood Avenue WAB 232, Boston, MA 02115, USA;
e-mail: phowe@hms.harvard.edu
Received 22 September 2004, in revised form 9 March 2005; published online 13 January 2006

Abstract. What determines an object's lightness remains unclear, but it is generally thought that the ratios of its luminance to the luminance of other objects in a scene play a crucial role because these ratios allow the relative reflectance of each object to be estimated, providing all the objects are under the same illumination. Because objects that lie in the same plane are typically illuminated equally, it has been suggested that it is the luminance ratios between coplanar objects that primarily determine lightness (Gilchrist, 1977 *Science* **195** 185 – 187; Gilchrist et al, 1999 *Psychological Review* **106** 795 – 834). An alternative hypothesis is that perceived illumination differences can affect lightness directly. As the studies that provided evidence for the coplanar ratio hypothesis always varied the illumination and the coplanar relationships simultaneously, it is unclear which hypothesis is correct. I measured the influence of each factor separately and found that the perceived illumination differences have a greater effect on lightness.

1 Introduction

In this paper I am concerned with the lightness of matte, achromatic objects. A problem faced by the visual system is that the luminance of an object is determined by both its reflectance and the illumination. Consequently, because in general the illumination is indeterminate, a target's reflectance cannot be estimated directly from its luminance. Instead, it has been suggested that a target's reflectance is estimated by measuring the ratio of its luminance to the luminance of other objects in the scene (eg Land and McCann 1971). This procedure would allow the relative reflectance of all the objects in a scene to be computed and then by anchoring one of these relative reflectance values to some absolute value, for example by assuming the most luminous object is white (Land and McCann 1971; Wallach 1976; for a review see Gilchrist et al 1999), the lightness of each object could be determined.

The above method is appropriate only if all objects are under the same illumination because otherwise their relative luminance values would be affected by the differences in illumination. For this reason, it is thought that the visual system measures luminance ratios only between objects that are coplanar, as typically only these objects experience the same illumination, a suggestion that is known as the *coplanar ratio hypothesis* (Gilchrist 1977). This hypothesis seems especially plausible, as it appears that coplanarity plays a role in a number of visual illusions (Adelson 1993; Taya et al 1995; Wishart et al 1997) and it is known that in other domains the visual system prefers to make comparisons within, as opposed to between, surfaces, eg motion (He and Nakayama 1994a, 1994b), visual search (He and Nakayama 1992), attention (He and Nakayama 1995), and texture (He and Nakayama 1994c; for a review see Nakayama et al 1995).

1.1 *Previous studies*

There have been several studies of lightness perception that would seem to be consistent with the coplanar ratio hypothesis. For example, Wolff (1933) employed a display where there were two identical targets, each positioned on a different background.

Because of simultaneous contrast (von Helmholtz 1867/1962, pages 269–278), the target on the dark background appeared lighter than the target on the light background. When Wolff moved the targets towards the observer, while keeping the background retinally adjacent to each target constant, the contrast effect disappeared. Consistent with the coplanar ratio hypothesis, this study would suggest that a background influences a target's lightness only when it is coplanar with the target.

A similar study has been reported by Kardos (1934, chapter 9). He employed a setup where a disk was positioned in front of a background that had a shadow cast on it. Initially, the disk was near the retinally adjacent background and appeared to be light-gray. As the disk was moved away from the background, while keeping the retinally adjacent background the same, the influence of the background on the lightness of the disk decreased and the disk became dark-gray.

Coren (1969) also provided evidence that seems to support the coplanar ratio hypothesis. In Coren's experiment, stereopsis was used to present a black cross in front of a white background. There was a gray test patch that was outside, but adjacent to, the black cross. In one condition, the gray test patch appeared to be in the plane of the white background; and in the other condition, in the plane of the black cross. Subjects were required to adjust the luminance of a Gerbrands differential rotor until it had the same lightness as the test patch in the two conditions. On average, the matching luminance in the latter condition was 7% larger than in the former. This result would seem to suggest that coplanarity might play a role in lightness perception. However, the effect was so small that it was not clear whether it was statistically significant.

Gogel and Mershon (1969) studied the effect of depth on lightness. To do this, they employed a variation of the Gelb effect. In the Gelb display, a large black disk is presented under strong illumination in an otherwise totally dark visual field. The disk is perceived to be either white or light-gray. A small white disk is then placed on the large disk. The large disk now appears much darker, a phenomenon known as whiteness contrast. Gogel and Mershon found that the induced darkness of the large disk decreased as the depth separation of the two disks increased. The Gogel and Mershon study was extended by Mershon and Gogel (1970) who verified that, consistent with the coplanar ratio hypothesis, it was the perception of a separation in depth, and not the small horizontal displacements necessary to produce stereopsis, that caused the effect.

Gilchrist (1977) also studied the influence of depth on lightness. His experiments are particularly notable for the large difference in lightness he was able to generate by changing the objects with which the target was perceived to be coplanar. In his first experiment, he was able to make a target appear to shift between two depth planes without altering its luminance. In the near-depth plane, the target appeared to be almost white, having a Munsell value of 9.0; and in the far-depth plane, it appeared dark-gray, having a Munsell value of just 3.5. In his second experiment, the display was designed so that on monocular viewing a target would appear to be coplanar with one object, but on binocular viewing with a different object. This change in the coplanar relationships resulted in an average shift in lightness of 4.5 Munsell units.

Gilchrist (1977) supplied an important caveat to the coplanar ratio hypothesis. He pointed out that, if lightness is a frame-of-reference phenomenon, then to change a target's lightness it is not sufficient to just move a target away from its retinally adjacent surface. Rather, it is necessary that the target must be perceived as a member of one coplanar ratio when it is seen in one position, but be perceived to be a member of a different coplanar ratio when seen in the other position. If the target is isolated in its own depth plane, the coplanar ratio hypothesis does not apply. In such situations, Gilchrist (1980) suggests that the visual system "defaults" to estimating a target's lightness by comparing its luminance to its retinally adjacent, but not coplanar, background.

Gilchrist (1980, page 533) supplied a second caveat: that the coplanar ratio hypothesis applies only when the luminance range in the scene is greater than 30 : 1. Taken together these two caveats explain why a number of other studies have failed to find a large effect of depth on lightness (Hochberg and Beck 1954; Epstein 1961; Gogel and Mershon 1969; Flock and Freedberg 1970; Julesz 1971; Gibbs and Lawson 1974; Dalby et al 1995). However, Zaidi et al (1997) also failed to find a depth effect, even though they appeared to satisfy both caveats: in their displays the target was never isolated and they used a luminance range of 82 : 1. When Gilchrist et al (1998) repeated the experiment of Zaidi et al using a 900 : 1 luminance range, they found an effect of depth on lightness and concluded that the luminance range employed by Zaidi et al was not sufficient for the coplanar ratio hypothesis to apply.

The findings of Gilchrist (1977, 1980) were replicated and clarified by Schirillo et al (1990). These authors pointed out that achromatic color matches can be made on the basis of either lightness or brightness. While their results for lightness followed the same pattern as Gilchrist's (1977, 1980), their results for brightness did not, indicating that the coplanar ratio hypothesis applied only to lightness matches. Although Schirillo and Shevell (1993) were able to verify the importance of the coplanar ratio hypothesis in lightness perception, the magnitude of the effect that they observed was considerably less than that obtained by Gilchrist (1977). They pointed out that in the Gilchrist displays the target always had a retinally adjacent coplanar object, but in their displays this was not the case. It seems that the coplanar ratio hypothesis can exert a stronger effect if it acts through objects that are retinally adjacent to the target. The special influence of retinally adjacent, but not necessarily coplanar, neighbors on a target's lightness is discussed in Schirillo and Arend (1995).

Although it is clearly not the only factor, the coplanar ratio hypothesis is now generally regarded as playing a particularly important role in lightness perception (Gilchrist et al 1999, page 805). However, it is also possible that differences in perceived illumination can affect a target's lightness directly (von Helmholtz 1867/1962, page 131). The previous studies that appeared to provide evidence supporting the coplanar ratio hypothesis either reported an effect that was so small that it was not clear if it was statistically significant (Coren 1969), or employed displays where changes in the coplanar relationships were always accompanied by changes in the apparent illumination, with the consequence that they could not be used to determine which factor was more important (Wolff 1933; Kardos 1934; Gogel and Mershon 1969; Mershon and Gogel 1970; Gilchrist 1977, 1980; Schirillo et al 1990; Schirillo and Shevell 1993). In this paper, I isolated and measured each factor independently.

2 Methods

Figure 1 shows the seven stereograms used in the experiment. Divergent fusers should fuse the left two columns and cross-fusers the right two. Each stereogram shows an oblong that appears to float above a checkerboard background. In the first two stereograms the oblong appears to cast a shadow onto its background, whereas in others it does not. In the first six stereograms there is a small gray square that in the left and right stereo half-images is adjacent to and below the oblong, whereas in the stereo half-images of the last stereogram it is adjacent to and above the oblong. I shall refer to this small gray square as the target. In all stereograms the target had the same luminance. The lightness differences between the targets in different stereograms were larger when the stereograms were displayed on a computer monitor as opposed to when they were displayed on paper. I measured the target's lightness for each stereogram.

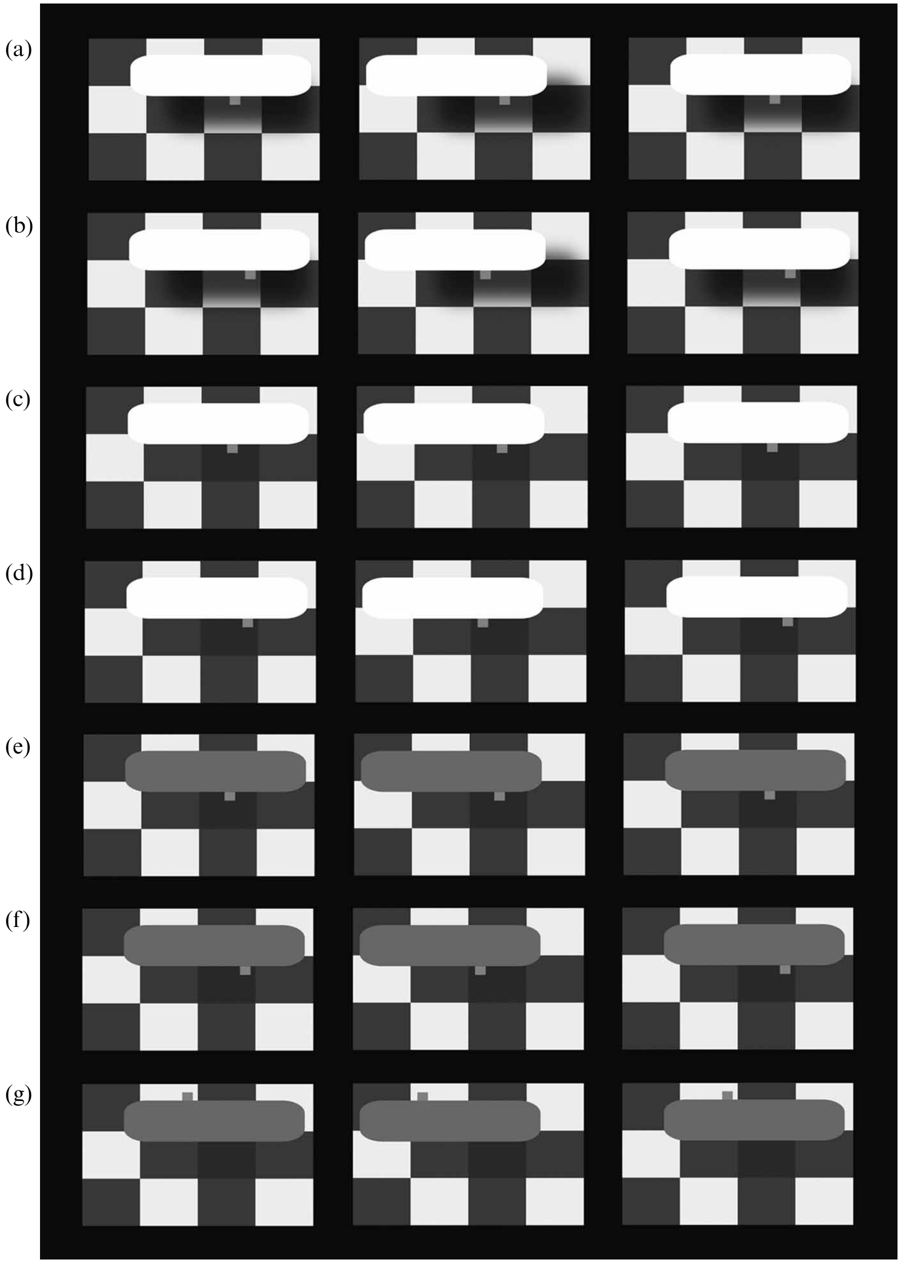

Figure 1. The seven stereograms used in the experiment. Divergent fusers should fuse the left two columns and cross fusers the right two. Once fused, in each stereogram there is an oblong that appears to float above the background. In the first six stereograms there is a small gray square below this oblong, whereas in the last stereogram it is above. The small gray square is referred to as the target and in all stereograms has the same luminance. The lightness of the target is different in different stereograms. The lightness differences were larger when the stereograms were displayed on a computer monitor. For each stereogram, I measured the target's lightness.

2.1 *Displays*

Each stereogram was viewed in turn through a haploscope (Old Delft Mark 3, The Netherlands). Next to the stereogram was an adjustable test patch positioned over a black-and-white checkerboard background. A typical display is shown in figure 2.

Figure 2. A typical display. When viewed through the haploscope the upper checkerboard was 3.8 deg high and 6.8 deg wide.

In this figure viewed through the haploscope the upper checkerboard was 3.8 deg high and 6.8 deg wide. The images were created with Adobe Illustrator® 10.0.3 (Adobe Systems, CA, USA) and the experiment was run in Matlab® 7.0.1 (The Mathworks Inc., MA, USA).

The stereograms were displayed on a 15-inch Dell Inspiron 8200 computer monitor in an otherwise darkened room. When viewed through the haploscope, only the computer screen could be seen. The monitor was calibrated for luminance, operated at 60 Hz and had a resolution of 1400×1050 pixels. The luminances were measured with a PhotoResearch® PR-1980A photometer and are accurate to within 2%. The luminance of the target was always 31.2 cd m^{-2} and the luminances of the white and dark checks of the upper checkerboard were 117.9 cd m^{-2} and 4.32 cd m^{-2} when the checks were fully illuminated, and 2.50 cd m^{-2} and 0.65 cd m^{-2}, respectively, when they were in the shadow cast by the oblong. The luminances of the light and dark checks of the lower checkerboard were 153.5 cd m^{-2} and 4.32 cd m^{-2}, respectively. The luminances of the oblong were 153.5 cd m^{-2} in stereograms (1a) – (1d) and 5.54 cd m^{-2} in stereograms (1e) – (1g). In stereograms (1a) – (1f) the luminance of the target's background was 2.50 cd m^{-2}, whereas in stereogram (1g) it was 117.9 cd m^{-2}. The luminance of the background surrounding the two checkerboards was 0.65 cd m^{-2}.

Gilchrist (1980, page 533) has suggested that the coplanar ratio hypothesis applied only to those displays where the luminance range is greater than 30 : 1. As the range of luminance values in the displays used in the following experiments was 236 : 1, the coplanar ratio hypothesis must apply.

2.2 *Procedure*

Five subjects participated in the experiment: one was the author and the other four were naive as to the purpose of the experiment. All procedures were in accordance with Harvard University and NIH guidelines for the use of human subjects. Subjects used a keyboard to adjust the test patch on a checkerboard background until it appeared "the same shade of gray" as the target in the stereogram. They were specifically requested to "ignore any differences in brightness or luminance between the two targets". These particular instructions were used so as to be consistent with Schirillo et al (1990) and Schirillo and Shevell (1993). Subjects practiced with the displays until they understood the difference between lightness and brightness judgments. None of the subjects had any problems making this distinction.

In half the trials the adjustable target was initialized to white, and in the other half to black. After the subject indicated whether the adjustable test patch appeared lighter or darker than the target, the luminance of the adjustable test patch was altered so as to make the lightnesses of the two objects more similar. This was done at a step-size that decreased during the course of the trial from a randomly assigned starting value. The trial was terminated when the subject indicated that the test patch had the same shade of gray as the target. To ensure that subjects were using the same criteria for making lightness judgments for all the stereograms, all the stereograms were viewed in a single session, with their trials interleaved at random. For each stereogram, sixteen measurements of the target's lightness were obtained, resulting in 112 trials per subject. By assuming that the white checks of the lower checkerboard had a reflectance of 90%, I was able to convert the luminance of the adjustable test patch into an equivalent reflectance. This reflectance was then converted into a Munsell value by using the standard tables (Newhall et al 1943). The results are shown in table 1. The first number in each cell is the mean Munsell value of the adjustable test patch when the subject perceived it to have the same lightness as the target. The second number is the standard error.

Table 1. This table shows for each subject and for each stereogram the Munsell value of the adjustable test patch when it appeared to have the same lightness as the target. The first and second numbers are the mean and standard error, respectively.

Subject	Stereogram						
	1a	1b	1c	1d	1e	1f	1g
PH	6.73 ± 0.09	5.65 ± 0.12	6.24 ± 0.09	5.24 ± 0.11	6.38 ± 0.09	6.13 ± 0.09	3.66 ± 0.11
NW	6.31 ± 0.14	5.25 ± 0.14	5.46 ± 0.13	4.90 ± 0.13	5.58 ± 0.13	5.19 ± 0.12	4.14 ± 0.11
YT	5.80 ± 0.22	5.26 ± 0.16	5.38 ± 0.20	5.20 ± 0.18	4.92 ± 0.17	5.25 ± 0.13	3.98 ± 0.17
CP	5.61 ± 0.29	4.35 ± 0.17	4.02 ± 0.16	3.83 ± 0.17	3.85 ± 0.11	4.04 ± 0.22	3.95 ± 0.19
AT	5.19 ± 0.17	4.62 ± 0.24	4.75 ± 0.13	4.58 ± 0.16	4.81 ± 0.14	4.71 ± 0.20	3.83 ± 0.39

At the end of the experiment, subjects were asked to describe the stereograms. They all stated that they perceived an oblong that appeared to float above a checkerboard background. They reported that in stereograms (1a) and (1b) the oblong appeared to cast a shadow onto the background, whereas in the other stereograms it did not. All subjects further reported that in stereograms (1a), (1c), and (1e) the target appeared to lie in the plane of the checkerboard, but in the other stereograms it appeared to lie in the plane of the oblong.

3 Results

3.1 *Figure 1a*

In this stereogram the target appears to lie on the checkerboard in the oblong's shadow. The target's luminance was 31.2 cd m^{-2} which corresponds to a Munsell value of 4.83. Subjects reported that the adjustable test patch had the same lightness as the target, when the adjustable test patch had a Munsell value considerably greater than the target. For each subject this result was found to be significant at the $p < 0.05$ level when a t-test was used. On average, this lightening corresponded to 1.1 Munsell units (cf table 1). Consistent with previous reports (von Helmholtz 1867/1962; Gilchrist et al 1983), this implies that, if two objects have the same luminance, then, everything else being equal, the one that appears to be less well illuminated will appear lighter.

3.2 *Figure 1b*

This figure is identical to figure 1a, except that the target appears to be in the same plane as the oblong and so no longer appears to be in the oblong's shadow.

This manipulation darkened the target, a result that for each subject was significant under a t-test at the $p < 0.05$ level. On average, the darkening corresponded to 0.90 Munsell units. Consistent with the findings of Gilchrist (1977, 1980), Schirillo et al (1990), and Schirillo and Shevell (1993), this shows that stereopsis can influence lightness.

It might be thought that this finding could be explained in terms of the coplanar ratio hypothesis (Gilchrist 1977). This hypothesis would predict that, by simultaneous contrast, the target in figure 1a, as it is coplanar with a dark background, should appear lighter than the identical target in figure 1b, as the latter is coplanar with a white oblong. Such a hypothesis begs the question why the observed effect was significantly smaller than that reported by Gilchrist (1977). In the first experiment of Gilchrist (1977) the ratio of the matching luminance in the two conditions was approximately 8.7 : 1, whereas in the current experiment, when we convert the Munsell values of table 1 into the equivalent luminance values, we find that the effect varied from 1.8 : 1 for subject CP, to 1.3 : 1 for subject AT with a mean of all subjects of 1.5 : 1. There appears to be at least three reasons for this discrepancy.

First, Gilchrist employed a physical setup where there were multiple depth cues, including occlusion, shadows, highlights, and variations in texture. Conversely, in the current investigation, the scene was simulated on a computer monitor and the only cue to depth was stereopsis. Such a suggestion would be consistent with the observations of Schirillo et al (1990) who found a reduced effect when they replicated the first experiment of Gilchrist (1977) on a computer monitor with a reduced set of depth cues. Whereas Gilchrist reported that the ratio of the luminance match in the near-condition versus the far-condition to be approximately 8.7 : 1, Schirillo et al found it to be only 3.5 : 1.

Second, it has been pointed out by Agostini and Bruno (1996) that lightness contrast effects are often larger on a computer monitor than on paper, even when the luminance range is the same in both cases. The authors attribute this to the lighting conditions. They point out that, in most experiments where a computer monitor was used, the room containing the monitor was typically dimly lit and so the monitor was the most luminous object. Conversely, in the experiments that used physical displays, typically the rest of the room was illuminated to the same degree as at least part of the display. Agostini and Bruno found that, when the lighting was arranged so that the physical display was illuminated much more strongly than the rest of the room—so-called Gelb conditions—the lightness contrast effect was as strong in the physical display as it was on the computer monitor. In Gilchrist (1977) it does not appear that the displays were illuminated much more strongly than the rest of the room. Consequently, Agostini and Bruno (1996) would suggest that lightness contrast be less strong in Gilchrist (1977) than on a computer monitor and, because lightness contrast tends to decrease lightness constancy, we might expect lightness constancy effects to be stronger in Gilchrist (1977) than in the current experiments. Since the results of Gilchrist (1977) were essentially due to visual system's attempts at lightness constancy we would therefore expect the effect reported by Gilchrist to be larger than that reported in the current experiments.

Third, in Gilchrist (1977) the luminance of the display varied over a range of approximately 2167 : 1, whereas in the displays employed in this paper the luminance range was only 236 : 1. When Schirillo et al (1990) reduced their luminance range from 2001 : 1 to 900 : 1, the effect decreased from 3.5 : 1 to 2.7 : 1.

Although the coplanar ratio hypothesis appears to be convincing, one can also attempt to explain lightness perception in terms of the perceived differences in the illumination (von Helmholtz 1867/1962, page 131). For two objects to reflect the same amount of light, the less illuminated one must be more reflective. As the target in figure 1a appears to be in a shadow, whereas that of figure 1b does not, and, because both targets have the same luminance, this explains why the former appears lighter than the latter.

We seem to have two possible explanations, one based on coplanar relationships and the other on the perceived illumination, why the target in figure 1a appears lighter than that in figure 1b. In the following experiments, I attempted to isolate and measure the relative importance of these two factors.

3.3 *Figure 1c*

As in figure 1a, the target in figure 1c appears to be in far-depth plane. Furthermore, the luminance of the target's background is the same in both stereograms and so the coplanar ratio hypothesis would predict that the two targets have the same lightness. However, unlike in figure 1a, the target does not appear to be in a shadow. Consequently, if the target's lightness is determined by the perceived illumination, then the target in figure 1c should be darker than the target in figure 1a. The latter hypothesis was found to be the case, with an average darkening of 0.8 Munsell units. Under a t-test at the $p < 0.05$ level this result was significant for each subject except YT. YT did show the effect, but the result did not reach significance, mainly because of the large standard errors associated with his measurements.

3.4 *Figure 1d*

Section 3.3 indicated that the lightness difference between the targets in figures 1a and 1b could be attributed to the differences in the perceived illumination. However, this does not prove that coplanarity per se, as distinct from perceived illumination differences, does not influence lightness. To investigate this possibility I used figure 1d. This figure is very similar to figure 1c and, in particular, the targets in the two figures appear to be illuminated equally. However, the target in figure 1d appears to be coplanar with the white oblong, whereas the target in figure 1c appears to be coplanar with a dark check of the checkerboard. If coplanarity is important, then the target in figure 1d should be lighter than that in figure 1c. For most subjects this was not found to be the case, and the result was significant under a t-test at the $p < 0.05$ level only for subjects PH and NW. It seems that coplanarity, as distinct from perceived differences in illumination, affects lightness for only some subjects.

3.5 *Figures 1e and 1f*

Figures 1e and 1f are identical to figures 1c and 1d, respectively, except that in the former the oblong is dark-gray whereas in the latter it is white. In figure 1e the target is on the checkerboard background where the most luminous objects are the white checks. In figure 1f the target is in the near-depth plane where it itself is the most luminous object. The anchoring theory of lightness perception attempts to explain the lightness of a target in terms of the luminance for the most luminous object with which the target is grouped (Gilchrist et al 1999). Consequently, according to this theory, the target of figure 1f should appear lighter than that of figure 1e. This was not found to be the case for any subject under a t-test at the $p < 0.05$ level.

3.6 *Figure 1g*

In all the previous experiments, the luminance of the target's retinally adjacent background was identical. In figure 1g, this was not the case with the target positioned over a white background. It might be thought that, owing to simultaneous contrast (von Helmholtz 1867/1962), the target in figure 1g should appear darker than the target in figure 1f as the former is retinally adjacent to a white background and the latter to a black background. However, Wolff (1933) found that, when a target is separated in depth from its retinally adjacent background, then simultaneous contrast does not occur, which would suggest that the targets in figures 1f and 1g should have the same lightness. A similar observation has been made by Gilchrist (1980, page 532). It is worth noting that this observation is contradicted by Julesz (1971) and Gibbs and Lawson (1974) but, as discussed in section 1.2, there are reasons to doubt the conclusions of these last two papers.

All subjects perceived the target in figure 1g to be darker than that in figure 1f. Under a t-test this result was significant at the $p < 0.05$ level for four subjects (PH, NW, YT, AT). It would seem that the observations of Wolff and Gilchrist do not apply. This might be because the difference in depth between the target and its background in figures 1g and 1f was not sufficient to remove all effects of simultaneous contrast.

4 Conclusion

It is generally thought that an object's lightness is determined primarily by those objects with which it is coplanar (Gilchrist et al 1999, page 805), a suggestion that is known as the coplanar ratio hypothesis (Gilchrist 1977). The studies that provided evidence supporting this hypothesis either reported an effect that was so small that it was not clear if it was statistically significant (Coren 1969), or employed displays where changes in the coplanar relationships were always accompanied by changes in the apparent illumination, with the consequence that they could not rule out the possibility that it was the perceived differences in illumination that caused the lightness difference (Wolff 1933; Kardos 1934; Gogel and Mershon 1969; Mershon and Gogel 1970; Gilchrist 1977, 1980; Schirillo et al 1990; Schirillo and Shevell 1993). As there have been a number of studies that have indicated that the inferred illumination has a significant effect on lightness (Gilchrist et al 1983; Knill and Kersten 1991; Logvinenko and Menshikova 1994; Williams et al 1998), this issue was clearly worth pursuing. The results of my experiments provided evidence that perceived differences in illumination could explain the effect of depth on lightness, and that changes in coplanarity that did not affect the perceived illumination had a significant effect on lightness for only two subjects.

These experiments should not be taken to imply that the reflectance of a target is estimated by comparing its luminance to the strength of the illumination (cf von Helmholtz 1867/1962). Among other problems with this approach, there is Hering's paradox (Hering 1874/1964; cited in Gilchrist 1980): given the luminance of the target, one would need to know its reflectance to infer the strength of the illumination, but the reflectance is what one is trying to determine in the first place. Instead, it seems that inferred illumination differences influence a target's lightness more than do coplanar relationships. This reasoning is not circular since it is sometimes possible to infer illumination *differences* without first estimating an object's reflectance (eg by detecting a shadow's penumbra, Kardos 1934). Once it has been determined that two targets are illuminated differently, then the lightness of each target could be estimated independently (Gilchrist et al 1999).

There are factors other than perceived illumination differences that influence a target's lightness. Of particular note is local contrast which is central to several theories of lightness (Grossberg and Todorović 1988; Blakeslee and McCourt 1999; Grossberg and Howe 2003; Blakeslee et al 2005). Comparing the targets in figures 1f and 1g, we see that they have the same illumination but different retinally adjacent backgrounds. Local contrast effects between the target and its background cause the target in figure 1f to appear much darker than the target in figure 1g. This difference in lightness, expressed as a percentage of the luminance of figure 1g, is larger than the lightness difference between any two of the other stereograms. It seems then that, for these displays, local contrast has a larger effect than the perceived illumination.

Other groups have emphasized the role of junction structure in lightness (Anderson 1997; Todorović 1997; Ross and Pessoa 2000). Of particular note is Todorović's manipulation of the Adelson corrugated Mondrian which showed that junction structure can cause a large difference in lightness even when the two targets appear to be illuminated equally. Recently, junction-based explanations of lightness have been disputed. Howe (2001) presented a variation of White's (1979) display which the junction accounts of Anderson (1997), Todorović (1997), and Ross and Pessoa (2000) could not explain. It seems that if one is to attempt to explain lightness in terms of junctions then one must acknowledge that junction structure can be modified by illusory contours (cf Watanabe and Cavanagh 1993). Bressan (2001) adopted a more extreme position and provided evidence that "junctions do not play any crucial role in lightness estimation" (page 1031). She did this by altering a number of well-known illusions that previously had been explained in terms of junction structure to show that the illusions persisted even when the junction structure was removed. It seems that junctions are at most just one factor that determines the object groupings, and it is these groupings that affect an object's lightness, perhaps in the manner suggested by the anchoring theory of lightness perception (Gilchrist et al 1999).

Acknowledgments. I would like to thank Charles Chubb, Bevil Conway, Tom Cornsweet, Alan Gilchrist, David Hubel, Margaret Livingstone, Dale Purves, and Aaron Seitz for helpful comments on previous versions of this manuscript. In addition, I received financial support from a Helen Hay Whitney Foundation postdoctoral fellowship and from grants NIH EY 13135 and ARO 46961 awarded to Margaret Livingstone.

References

Adelson E H, 1993 "Perceptual organization and the judgment of brightness" *Science* **262** 2042 – 2044

Agostini T, Bruno N, 1996 "Lightness contrast in CRT and paper-and-illuminant displays" *Perception & Psychophysics* **58** 250 – 258

Anderson B L, 1997 "A theory of illusory lightness and transparency in monocular and binocular images: the role of contour junctions" *Perception* **26** 419 – 453

Blakeslee B, McCourt M E, 1999 "A multiscale spatial filtering account of the White effect, simultaneous brightness contrast and grating induction" *Vision Research* **39** 4361 – 4377

Blakeslee B, Pasieka W, McCourt M E, 2005 "Oriented multiscale spatial filtering and contrast normalization: a parsimonious model of brightness induction in a continuum of stimuli including White, Howe and simultaneous brightness contrast" *Vision Research* **45** 607 – 615

Bressan P, 2001 "Explaining lightness illusions" *Perception* **30** 1031 – 1046

Coren S, 1969 "Brightness contrast as a function of figure – ground relations" *Journal of Experimental Psychology* **80** 517 – 524

Dalby T A, Saillant M L, Wooten B R, 1995 "The relation of lightness and stereoscopic depth in a simple viewing situation" *Perception & Psychophysics* **57** 318 – 332

Epstein W, 1961 "Phenomenal orientation and perceived achromatic color" *Journal of Psychology* **52** 51 – 53

Flock H R, Freedberg E, 1970 "Perceived angle of incidence and achromatic surface color" *Perception & Psychophysics* **8** 251 – 256

Gibbs T, Lawson R B, 1974 "Simultaneous brightness contrast in stereoscopic space" *Vision Research* **14** 983 – 987

Gilchrist A L, 1977 "Perceived lightness depends on perceived spatial arrangement" *Science* **195** 185 – 187

Gilchrist A L, 1980 "When does perceived lightness depend on perceived spatial arrangement?" *Perception & Psychophysics* **28** 527 – 538

Gilchrist A L, Bonato F, Annan V, Economou E, 1998 "Depth, lightness (and memory)" *Investigative Ophthalmology & Visual Science* **39** Supplement, S671

Gilchrist A, Delman S, Jacobsen A, 1983 "The classification and integration of edges as critical to the perception of reflectance and illumination" *Perception & Psychophysics* **33** 425 – 436

Gilchrist A, Kossyfidis C, Bonato F, Agostini T, Cataliotti J, Li X, Spehar B, Annan V, Economou E, 1999 "An anchoring theory of lightness perception" *Psychological Review* **106** 795 – 834

Gogel W C, Mershon D H, 1969 "Depth adjacency and simultaneous contrast" *Perception & Psychophysics* **5** 13 – 17

Grossberg S, Howe P D, 2003 "A laminar cortical model of stereopsis and three-dimensional surface perception" *Vision Research* **43** 801 – 829

Grossberg S, Todorović D, 1988 "Neural dynamics of 1-D and 2-D brightness perception: a unified model of classical and recent phenomena" *Perception & Psychophysics* **43** 241 – 277

He Z J, Nakayama K, 1992 "Surfaces versus features in visual search" *Nature* **359** 231 – 233

He Z J, Nakayama K, 1994a "Apparent motion determined by surface layout not by disparity or three-dimensional distance" *Nature* **367** 173 – 175

He Z J, Nakayama K, 1994b "Perceived surface shape not features determines correspondence strength in apparent motion" *Vision Research* **34** 2125 – 2135

He Z J, Nakayama K, 1994c "Perceived textures: Beyond filtering" *Vision Research* **34** 151 – 162

He Z J, Nakayama K, 1995 "Visual attention to surfaces in three-dimensional space" *Proceedings of the National Academy of Sciences of the USA* **92** 11155 – 11159

Helmholtz H von, 1867/1962 *Treatise on Physiological Optics* volume 3 (New York: Dover, 1962); English translation by J P C Southall for the Optical Society of America (1925) from the 3rd German edition of *Handbuch der physiologischen Optik* (first published in 1867, Leipzig: Voss)

Hering E, 1874/1964 *Zur Lehre vom Lichtsinn* (1874, Vienna: Gerolds Söhne) [Outlines of a *Theory of Light Sense* English translation by L M Hurvich, D Jameson (1964, Cambridge, MA: Harvard University Press)]

Hochberg J E, Beck J, 1954 "Apparent spatial arrangement and perceived brightness" *Journal of Experimental Psychology* **47** 263 – 266

Howe P D, 2001 "A comment on the Anderson (1997), the Todorović (1997), and the Ross and Pessoa (2000) explanations of White's effect" *Perception* **30** 1023 – 1026

Julesz B, 1971 *Foundations of Cyclopean Perception* (Chicago, IL: Chicago University Press)

Kardos L, 1934 *Ding und Schatten [Object and Shadow] Zeitschrift für Psychologie* Ergänzungsband 23 (translated by D Todorović; edited by A Gilchrist)

Knill D C, Kersten D, 1991 "Apparent surface curvature affects lightness perception" *Nature* **351** 228 – 230

Land E H, McCann J J, 1971 "Lightness and retinex theory" *Journal of the Optical Society of America* **61** 1 – 11

Logvinenko A, Menshikova G, 1994 "Trade-off between achromatic colour and perceived illumination as revealed by the use of pseudoscopic inversion of apparent depth" *Perception* **23** 1007 – 1023

Mershon D H, Gogel W C, 1970 "Effect of stereoscopic cues on perceived whiteness" *American Journal of Psychology* **83** 55 – 67

Nakayama K, He Z J, Shimojo S, 1995 "Visual surface representation: A critical link between lower-level and higher-level vision" *Vision Cognition* Eds S E Kosslyn, D N Osherson (Cambridge, MA: MIT Press) volume 2, pp 1 – 70

Newhall S M, Nickerson D, Judd D B, 1943 "Final report of the O.S.A. subcommittee on the spacing of the Munsell colors" *Journal of the Optical Society of America* **33** 385 – 418

Ross W D, Pessoa L, 2000 "Lightness from contrast: a selective integration model" *Perception & Psychophysics* **62** 1160 – 1181

Schirillo J A, Arend L E, 1995 "Illumination change at a depth edge can reduce lightness constancy" *Perception & Psychophysics* **57** 225 – 230

Schirillo J, Reeves A, Arend L, 1990 "Perceived lightness, but not brightness, of achromatic surfaces depends on perceived depth information" *Perception & Psychophysics* **48** 82 – 90

Schirillo J A, Shevell S K, 1993 "Lightness and brightness judgments of coplanar retinally noncontiguous surfaces" *Journal of the Optical Society of America A* **10** 2442 – 2452

Taya R, Ehrenstein W H, Cavonius C R, 1995 "Varying the strength of the Munker – White effect by stereoscopic viewing" *Perception* **24** 685 – 694

Todorović D, 1997 "Lightness and junctions" *Perception* **26** 379 – 394

Wallach H, 1976 *On Perception* (New York: Quadrangle/The New York Times Book Co.)

Watanabe T, Cavanagh P, 1993 "Transparent surfaces defined by implicit X-junctions" *Vision Research* **33** 2339 – 2346

White M, 1979 "A new effect of pattern on perceived lightness" *Perception* **8** 413 – 416

Williams S M, McCoy A N, Purves D, 1998 "The influence of depicted illumination on brightness" *Proceedings of the National Academy of Sciences of the USA* **95** 13296 – 13300

Wishart K A, Frisby J P, Buckley D, 1997 "The role of 3-D surface slope in a lightness/brightness effect" *Vision Research* **37** 467 – 473

Wolff W, 1933 "Über die kontrasterregende Wirkung der transformierten Farben" *Psychologische Forschung* **18** 90 – 97

Zaidi Q, Spehar B, Shy M, 1997 "Induced effects of backgrounds and foregrounds in three-dimensional configurations: the role of T-junctions" *Perception* **26** 395 – 408

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 35 2006

www.perceptionweb.com