SPATIAL AND PHOTOMETRIC FACTORS

MODULATING THE EFFECT OF DEPTH ON LIGHTNESS

by

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ABSTRACT OF THE DISSERTATION

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According to the coplanar ratio principle (CRP), when the luminance range in the image is larger than 30:1 the lightness of a target surface depends on the luminance ratio between that target and its adjacent, coplanar neighbor. This conclusion was based on experiments (Gilchrist, 1977) using a dihedral corner display in which a change in the perceived spatial position of a target produced large changes in its perceived lightness, with no significant change in the observer's retinal image. Using variations of this dihedral display, a series of experiments was conducted to test a group of conflicting claims made by CRP, the anchoring theory (Gilchrist et al., 1999) and other writers (e.g. Kardos, 1934, Howe, 2006) concerning the role of coplanarity, adjacency, surroundedness, articulation, and luminance range.

Generally consistent with the predictions of the anchoring theory, the results show the following: (1) Articulation can substantially increase the depth effect. (2) Target lightness depends, not simply on its adjacent coplanar luminance, but on the highest luminance in its plane, irrespective of its position relative to the target. (3) When two or more levels of illumination are present on a plane, target lightness depends on the highest luminance in its framework of illumination, not on the highest luminance in its plane. (4)

The size of the depth effect depends on the luminance ratio between the highest luminance values in the two planes, not on the overall luminance range across the planes. Thus strong depth effects can be obtained with a luminance range no greater than 30:1. (5) Surface continuity within a plane is necessary for the operation of coplanar ratios, although surroundedness can partially substitute for continuity, but only within the brightly illuminated plane.

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I Introduction

1. The role of depth in lightness perception in the classic theories of lightness: from Helmholtz's unconscious inference to Wallach's ratio principle

Lightness perception is the process by which the visual system attributes the value of certain shades of gray, from white to black, to the achromatic surfaces in the environment. Lightness, or the perceived shade of gray, is a psychological variable equivalent to the visual experience of surface reflectance. Reflectance is a physical variable that refers to the proportion of the incident light that a surface reflects.

However, information about surface reflectance is not directly available to the visual system. Instead, the only information available from the retinal image is luminance, the total amount of light that a surface reflects, which is co-determined by the reflectance and the incident illumination. While the reflectance is an invariant property of the surface that can have a certain value from 3% (black) to 90% (white), the illumination is variable, over time and over space, across an indefinite range. Thus, obtaining information about surface reflectance from luminance only is an under-constrained task for the visual system, equivalent to solving an equation with two unknowns: any luminance value can be the product of any surface reflectance under some level of illumination.

If lightness depended on luminance only, then it would appear to change every time the level of illumination changes. Contrary to this, lightness seems to be more correlated with the properties of the distal rather than the proximal stimulus: surfaces yielding the same luminance can be perceived as different in lightness, while the lightness of a single surface, yielding different luminance values under different illuminations, is perceived as relatively constant (Katz, 1935; Arend & Goldstein, 1987; Brainard, 1998). Understanding how the visual system perceives surface lightness as constant, despite variations in illumination and viewing conditions, is the main problem of lightness perception.

The tendency of the visual system to detect constant properties of the object, such as shape, size, color, reflectance or position in space, rather then variable properties of their retinal projection that depend on viewing conditions in a given moment, is an important feature of the visual system. It is reflected in a variety of perceptual constancies: perceived size corresponds to the actual size of the object, despite the changes of the visual angle it subtends, perceived shape of the object corresponds to its actual shape despite the changes in shape of its retinal projection, etc. Such a tendency is a logical necessity for the system whose main goal is to derive a veridical representation of three-dimensional objects and their stable characteristics (such as size, color or lightness, position, shape) in the three-dimensional environment, from the pattern of light in the retinal image, which is constantly changing (Marr, 1982).[1] The exact mechanism through which the visual system achieves this goal, having the retinal image as the only input, is still not known.

If the goal of the visual system is to represent objects in three-dimensional space, it is logical to assume that the perception of object features will depend on the perception of object spatial position. In very early days of scientific interest in lightness perception,

[1] The idea that the goal of visual system is to identify constant properties of the objects has been repeatedly emphasized throughout the history of vision science: "Seeing is not the matter of looking at light waves as such, but of looking at external things mediated by these waves", writes Hering (1874/1964, p. 23); "We generally perceive, not light and shadow, but objects in space", writes Mach (1922/1959, p. 208); von Helmholtz (1866/1924, p. 286) makes the same point when talking about color perception: "Colors have their greatest significance for us in so far as they are properties of bodies and can be used as marks of identification of bodies".

Ernst Mach provided empirical evidence for this logical argument. His bent-card illusion is a wonderfully simple, yet convincing demonstration that lightness of the object depends on its perceived position. When a folded piece of white paper is placed horizontally, facing downward, and illuminated from one side, it appears as a tent whose two sides, equal in lightness, are differently illuminated. However, the same luminance distribution can yield a different percept when the card is viewed monocularly; then it appears as an open book, standing upright, with two sides different in lightness and equally illuminated (Mach, 1922/1959). The retinal image is the same in these two appearances; only the perceived spatial arrangement changes.

Early accounts of lightness constancy, that originated in the second half of the XIX century, didn't systematically study the effect of depth on lightness. This can be understood in the context of predominant scientific trends at the time. After understanding the physical and physiological mechanisms of the formation of the image on the retina, in the XVII century, the focus of attention of early vision scientists was on the proximal stimulus. This is reflected in the theoretical account known as the constancy hypothesis (Koffka, 1935) or the doctrine of local determination (Gilchrist, 2006) according to which, given that the retinal input is the only information the visual system directly obtains from the environment, the visual experience must be determined by the retinal stimulation, based on a one-to-one mapping. This implies that a constant retinal stimulation will always yield a constant percept, and changes in the retinal stimulation will yield equivalent changes in perception. The phenomenon of lightness constancy directly contradicts this idea – and to account for it (without rejecting the doctrine of local determination!) hypothesizing additional processes was required.

Herman von Helmholtz (1866/1924) proposed that lightness perception is a two-step process: while in the first step a sensation is formed, corresponding to the retinal stimulation (as proposed by the doctrine of local determination), in the second the percept, corresponding to the object characteristics, is derived from the sensation based on the past experience. He assumed that the lifetime experience of seeing objects of particular reflectance under different illuminations, yielding different luminance values, is stored in the form of associations, enabling the visual system to judge actual object reflectance under any given illumination. Helmholtz's account thus implies that the visual system is able to infer the intensity and chromaticity of the illumination, and discount this value from the luminance value to obtain object reflectance. The idea that the visual system is able to unconsciously infer the illumination in a scene, based either on past experience[2] or on other cues available in the retinal image[3], has been extremely influential and repeatedly revived in lightness and color research ever since.

Hering (1874/1964) strongly criticized Helmholz's account of constancy as paradoxical: to obtain the reflectance value from the luminance, the visual system would need to know the value of illumination – which, in turn, can be derived from luminance only if the reflectance value is known. Instead, Hering argued, lightness constancy could be fully explained by relying on three physiological mechanisms: pupil size, accommodation and the retinal mechanisms of excitation and inhibition, and on one

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[2] Gilchrist (2006) points out that the inference of reflectance from luminance based only on the past experience cannot be sufficient explanation for lightness and color constancy, because it does not explain how the visual system can make initial differentiation between relative contributions (in terms of lightness and chromaticity) of illumination and reflectance in the proximal stimulus. In other words - how is the red object under white illumination distinguished from the white object under red illumination, when both can have the same luminance.

[3] von Helmholtz (1868/1924) implies that the mean chromaticity and the mean luminance in the image can serve as cues to illumination (cited according to Gilchrist, 2006)

psychological factor similar to Helmholtzian past experience: memory color. While physiological factors aim to minimize the change in the absolute luminance by nullifying the change in illumination, memory color, associated with the object in the course of previous viewings corrects the sensation toward the objective value.

Neither Helmholtz nor Hering explicitly discussed the role of depth in lightness perception. Hering's account, predominantly based on the retinal image, implicitly rejects it: as long as the retinal image remains constant, changes in perceived depth of an object should not affect perceived lightness. Yet, the Mach bent-card illusion demonstrates the opposite. The Mach card illusion cannot be explained by invoking memory color either, given that the effect of the immediate past experience of card lightness directly contradicts the new percept. Interestingly, Hering seemed to be fully aware of this type of phenomenon; he wrote about the Mach card illusion: "Here…with the different localization there is also a difference in apparent color, in spite of the identical light intensities of the two surfaces and unchanged tuning of the eyes" (1874/1964, p. 11). However, he did not offer a coherent explanation for it, nor did he indicate that it was contradictory to his own theoretical stance.[4]

The role of depth in lightness perception, although not explicitly discussed, is implied in Helmholtz's account: if the visual system takes the illumination into account, then the inference of spatial and temporal variation in illumination is important for lightness perception. Helmholtz himself did not propose an exact mechanism via which the spatial distribution of the illumination is estimated, but has provided a powerful inspiration to the other vision scholars to create testable models of visual system taking illumination

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[4]Rather, he continues:"…the neural visual mechanism reacts differently to the same radiation, because in the two cases different reproductions are aroused by the secondary conditions, most often optical ones" (Hering, 1874/1964, p.11).

into account. One of the first such models became known as the albedo hypothesis (Woodworth, 1938) and, due to its logical coherence and the precise (inverse) correspondence to the physical process of image creation, it gained considerable attention. The core idea of the albedo hypothesis is the following: if the system receives only information about the luminance, which is codetermined by surface reflectance and incident illumination, and despite the variations in the illumination (thus, luminance) it yields a percept that corresponds relatively accurately to surface reflectance, then, it logically follows that the system is able to infer the level of illumination, based on which it can recover the information about the reflectance (Woodworth, 1938; Flock & Freedberg, 1970). In other words, to the extent to which the visual system is able to accurately estimate the illumination, the surface lightness will be perceived accurately.

Thus, to understand lightness perception, it is necessary to explain how the illumination is estimated. The emphasis of this approach, also referred to as the empiricist inferential cue theory (Flock & Freedberg, 1970) is, thus, on identifying the cues in the retinal image that reveal the information about illumination necessary to achieve lightness and color constancy. Within such approach the importance of spatial relations is clearly recognized. Lightness depends not only on the estimated overall intensity and chromaticity of the illumination, but also on spatial relations such as distance, position and orientation of the surface relative to the light source. This information may be available to the visual system from the numerous cues within the image: luminance ratios, shape and location of attached and cast shadows, luminance gradients, specular highlights, average and/or highest luminance in the scene or the direct visibility of the light source (Flock & Freedberg, 1970; Ripamonti et al., 2004; Bloj et al., 2004; Boyaci et al., 2003, 2006).

Note that both Hering's and Helmholzian theoretical approaches focused on retrieving information about surface lightness from the absolute luminance available in the retinal image. Ernst Mach (1922/1959) was one of the first to point out that, although the absolute luminance values are constantly changing, their relationship remains constant; thus, the solution to the constancy problem may lie in the invariant luminance ratios, which are also available in the retinal image. This idea was also proposed by Koffka (1935) who, in the spirit of Gestaltist emphasis on the importance of the perceptual structure, argued that surface lightness depends on the luminance relations among surfaces in the field, and that the strength of that dependence will be determined by perceptual grouping: "The more x belongs to the field part y, the more will its whiteness be determined by the gradient xy [luminance ratio of x and y], and the less it belongs to the part z, the less will its whiteness depend on the gradient xz [luminance ratio of x and z]" (Koffka, 1935, p. 246).

Unlike their predecessors, the Gestaltists emphasized the role of depth on lightness in their theoretical discussions and demonstrated it in their experimental work: if lightness depends on perceptual structure, then depth will play an important role in lightness computation. Koffka talked about coplanarity as one of the main grouping factors[5] and Kardos (1934), Wolff (1933), Katona (1935) conducted the first systematic studies exploring the effect of depth on lightness.[6]

[5] "…two parts at the same apparent distance will, ceteris paribus, belong more closely together than field parts organized in different planes" (Koffka, 1935, p. 246).

[6] Both the experimental findings and the theoretical ideas of the Gestaltists are crucial to many aspects of the work I will present. They will be described and discussed in detail at relevant points later in the text.

However, the first empirical evidence that perceived lightness depends on relative, and not absolute, luminance was produced in a simple, yet striking demonstration by Wallach (1948). Using a pair of slide projectors whose light intensity could be varied Wallach created a stimulus consisting of two adjacent surfaces – a disk and an annulus surrounding it. When the luminance of the annulus was varied, while the luminance of the disk was kept constant, the perceived lightness of the disk changed, suggesting that lightness depends on relative luminance. Depending on the luminance ratio of the disk and the annulus, the disk could appear as any shade of gray from black to white.

In a formal experiment, Wallach used two pairs of disk-annulus stimuli. In one pair both the luminance of the ring and the annulus were fixed, yielding a fixed luminance ratio. In the other pair, the luminance of the annulus was also fixed, at a value different from that in the fixed pair, while the luminance of the disk could be varied. The observer task was to adjust the luminance of the variable disk, so that it appears equal in lightness to the disk in the fixed pair.

If lightness depended on absolute luminance, the luminance match for the variable disk should be close to the luminance of the fixed disk. If it depended on relative luminance, the luminance match should be close to the level that yields approximately the same luminance ratio as in the fixed pair. The results clearly supported the relative luminance outcome: disk luminance matches were almost exact ratio matches. Based on these findings, Wallach formulated the ratio principle according to which the surface lightness depends on the luminance ratio between the target surface and its surround (Wallach, 1948, 1963).

Wallach's ratio principle suggests that luminance ratios that remain constant while the overall illumination level changes provide a sufficient basis for lightness constancy and that estimating or discounting the illumination, as Helmholzian theories would suggest is not necessary.

Despite its simplicity and its ability to account for lightness constancy only in terms of invariants in the retinal image, because of which it was viewed as support for the physiological theories of lightness (Cornsweet, 1970; Jameson & Hurvich, 1964), further research pointed to some significant limitations of the ratio principle:

(1) It worked best within the standard reflectance range, under uniform illumination and only for decrements, but not increments (Cornsweet, 1970; Heinemann, 1955; Gilchrist, 2006).

(2) It could not predict absolute lightness values without "an anchoring rule", that would relate the luminance ratios to absolute lightness scale (Gilchrist, 2006).

(3) Formulated to account for lightness variation within extremely simple stimuli, it stressed the importance of the luminance ratio of target surface and its immediate surround only, neglecting the role that other, remote luminance values in the visual field may have in lightness computation (Land & McCann, 1971; Gilchrist, 2006).

(4) Defined strictly in terms of luminance variation in the proximal stimulus, it could not distinguish between reflectance and illumination edges in the image.[7]

(5) It neglected any role that depth perception could have on lightness: as long as the luminance ratios in the image are held constant, the perceived lightness will remain the same, no matter what is the structure of the distal stimulus that caused it. In its literal

[7] Note the absurdity contained in the Wallach experimental design itself: the stimuli created using illumination variation served as the basis for studying how the visual system treats the variation in reflectance (Palmer, 1999).

application, the ratio principle would, therefore, predict that a surface lightness would change every time that surface is seen against a background of different luminance, which, as our everyday experience assures us, clearly not the case. Contrary to Wallach ratio principle, Wolff (1933) showed that perceived depth has a significant effect on perceived color, even when retinal ratios remain the same. When two equiluminant targets are placed in front of retinal backgrounds different in luminance, they appear equal in lightness/color when perceived as standing in front of their backgrounds; but, when hung on thin threads, so they appeared as lying in the plane of their backgrounds, they were perceived as different. This finding suggests that (1) perceived coplanarity is a necessary condition for the contrast effect and (2) that the same retinal ratios can yield different perceived lightness/color depending on perceived depth.

However, the work of Wolff (1933) and the other Gestaltists (Koffka, 1935; Kardos, 1934; Katona, 1935) was not widely known at the time of Wallach's experiments. Forgotten or neglected, many of their ideas and findings waited to be reinvented and rediscovered.

2. Some (weak) empirical evidence of the depth effect on lightness

The question following from Wallach ratio principle, whether constant retinal ratios always produce constant perceived lightness, irrespective of the spatial relation in the distal stimulus, inspired a landmark experiment by Hochberg and Beck (1954), which initiated a vigorous debate about the role of depth in lightness perception.

Hochberg and Beck devised an original experimental paradigm that allowed them to vary the perceived position of the target surface, by changing the viewing conditions, while keeping the retinal image constant. An upright gray cardboard trapezoid, which served as a target in the experiment, was placed in a stimulus chamber covered with black cloth and illuminated from above by a light source not visible to the observer. When viewed monocularly through a pinhole in the vertical panel, the target appeared as a horizontal square, lying flat on the black surface. However, the target appeared veridically in depth when either (1) the experimenter moved a rod directly behind it or (2) it was moved through small horizontal arcs or (3) the observer looked at the scene binocularly. The same group of observers judged the target lightness in the two perceived positions (vertical and horizontal) and unanimously reported that it appeared darker when perceived as the horizontal square, facing the light source and lighter when perceived as the upright trapezoid.[8]

Hochberg and Beck (1954) attributed this change in perceived lightness to the change in perceived position of the target relative to the light source. When the light source was moved to the front, the target appeared darker in the vertical perceived position, directly facing the light source, and not in the horizontal one. When the light was coming from the side, it would equally illuminate the target in both perceived positions and the target lightness did not change. Hochberg and Beck assumed that information about the perceived direction of the illumination was available to the visual system from the shadows cast by the contextual objects (cubes) added to the experimental setup: in the preliminary studies, when the cubes were not present, the target did not change in lightness with the change in perceived position.

These results, showing that the same luminance ratios can yield different perceived lightness, suggests that any account of lightness based solely on retinal ratios

[8] The Hochberg & Beck study describes the effect of perceived position on lightness only in qualitative terms. Data on the size and stability of the effect are available from numerous replications.

is, at best, incomplete. Instead, the Hochberg and Beck interpretation of the results seems to fit better with the Helmholtzian, inferential explanation and the albedo hypothesis: the visual system uses cues available in the image to detect the position and the intensity of the light source and constrains lightness computation by taking into account this information. When the target is perceived as perpendicular to the direction of illumination, it will be perceived as darker, because the lower target lightness is needed to account for the same luminance, than when it is perceived to be parallel to the direction of illumination (Hochberg & Beck, 1954).

The Hochberg and Beck study had a significant influence in the field – both because of its creative, yet simple, experimental paradigm and the challenge it put to physiological theories dominant at the time. It inspired numerous replications and a lively debate between the theorists supporting Helmholzian, higher-level explanations of lightness perception and those emphasizing processes occurring on the retinal level.

Epstein (1961) failed to replicate Hochberg and Beck (1954), using slightly different stimuli but the same experimental design, which led him to conclude that the "Hochberg-Beck findings may be peculiar to the specific experimental situation" (Epstein, 1961, p. 53).

Beck (1965) replicated the original study, aiming to test if the change in target lightness can be explained solely as a function of the perceived position of the target relative to the light source. According to the albedo hypothesis, when target luminance is held constant, (1) a perceived change in lightness would always occur with a change of perceived illumination and (2) that change in lightness would be proportional to the perceived change in illumination. Due to its formalization, the albedo hypothesis can yield relatively precise predictions about the effect of perceived position (relative to the light source) on lightness. To test this prediction Beck measured the effect of perceived position (horizontal vs. vertical) on target lightness while varying the distance of the target from the light source. As the target moves farther and farther from the light source, the perceived change in lightness resulting from the change in perceived position should be smaller, because the difference in intensity of illumination falling upon the target in the two perceived positions is smaller. At four distances, the predicted change in target lightness varied from 950%, when the target was closest to the light source to 0%, when the target was farthest from the light source. However, despite “ample cues present to indicate the direction of illumination and its distribution” (Beck, 1965, p. 176) the change in the perceived position yielded a significant change in lightness only for the closest target and the size of the change was far smaller than predicted by the albedo hypothesis (0.5 Munsell steps, equivalent to 33% change, instead of predicted 950% change).

Beck (1965) obtained similarly small effects, using a variant of the Mach card display: the shadowed side of the card changed in lightness with the change in perceived depth only for 0.5 - 1.25 Munsell units (15% instead of predicted 50% and 52% instead of predicted 580% change). Beck concluded that the change in apparent illumination is not sufficient to account for the change in perceived lightness as the albedo hypothesis suggested. Instead, he pointed out that the change in perceived position causes a global perceptual re-organization of the stimulus. According to Beck there are multiple factors determining the perceptual organization (contrast, adaptation, contour integration, type of edges, cues related to the stimulus pattern, illumination and apparent spatial, as well as memory, set and attitude of the observer), but “exactly how these factors cooperate in achieving an integration of the stimulus pattern determined by the peripheral sensory processes is not known" (Beck, 1965, p. 179).

Flock and Freedberg (1970) replicated the Hochberg and Beck study, varying the amount of cues available to the visual system, to test if the accuracy of the albedo hypothesis predictions depends on the number of cues available in the scene. Similarly to Beck (1965), they obtained a change in perceived lightness far smaller than that predicted by the albedo hypothesis: only 0.25 - 0.5 Munsell units, corresponding to the change in position of 1.4 - 4.9° relative to the light source, instead of the actual 90° (Flock & Freedberg, 1970). Although not significant, the change in lightness was greater with than without cues such as (1) attached and cast shadows produced by the cubes, (2) highlights and (3) illumination gradient (more visible with the white background than the black background). Thus, the authors concluded that "the trends…give some support to relative albedo theory and to the more general inferential cue theory" (Flock and Freedberg, 1970, p. 256).

Redding and Lester (1980) conducted an identical experiment to that of Flock and Freedberg (1970), only without cubes as potential cues to illumination and got the same size of the effect (0.1 to 0.5 Munsell steps, often non-significant). Also, contrary to the results of Flock & Freedberg, the effect size was consistently smaller with the white than with the black background, suggesting that even visibility of the illumination gradient does not have an effect on perceived change in lightness. Surprisingly, despite small and inconsistent effects, the authors concluded that the direction of the darkening effect is consistent with the albedo hypothesis (Redding & Lester, 1980).

Another group of studies explored the effects of depth on lightness using a different experimental paradigm that involved stereoscopic presentation of well-known lightness illusions. Typically, in one of the conditions of these studies, the test surface, whose lightness is misperceived, is presented in a different plane than the surface inducing the illusion and the size of this stereo version of illusion is compared to the original in which all the elements are presented in the same plane. The logic behind this paradigm is similar to the one used in the Hochberg & Beck experiment and its replications: in the two conditions, the perceived depth of elements changes but the retinal image remains the same.[9] If the tested illusion is caused (only) by the processes occurring on the retinal level (e.g. lateral inhibition), as is often hypothesized, then the strength of the illusion should not change with a change in the perceived depth of its elements.

In one of the first studies of this kind Gogel and Mershon (1969, also Mershon & Gogel, 1970; Mershon, 1972), studied the effect of perceived depth on the Gelb effect. When a piece of black paper is suspended in midair and illuminated by a hidden spotlight it appears white; however, it significantly darkens, when a piece of real white paper is placed on or adjacent to it, within the spotlight. If this darkening is simply a contrast phenomenon (Stewart, 1959) that can be accounted for in terms of retinal inhibition, then any change in perceived depth of the white inducing paper relative to the black Gelb target should not change the amount of darkening, as long as the retinal image remains the same.

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[9] It should be noted that the retinal image is approximately the same across conditions; to achieve the change in depth using a stereoscope, critical elements of the illusion have to be laterally displaced. However, such changes are minimal and there is no evidence that, on their own, they can cause a change in the percept. Mershon and Gogel (1970) show that the lateral displacement, which is not followed by the change in depth, doesn't affect the size of the illusion.

To test this prediction Gogel and Mershon (1969) varied the perceived depth of a small white disk relative to a large Gelb disk. While always retinally adjacent, the white disk could appear either coplanar to the Gelb disk or in front of it, at two different distances. They found a significant difference in darkening of the black disk as a function of both perceived and actual distance between the two disks. Darkening was the biggest when the white disk appeared coplanar to Gelb disk and it was reduced as the perceived distance between disks increased. However, the size of this difference, although consistently significant, was relatively small: up to 1 Munsell step.

The authors explain the results by invoking Gogel's adjacency principle, which applied to lightness, can be considered a variant of Koffka's principle of belongingness:[10] "the effectiveness of cues between objects in determining perceived object characteristics is inversely related to the relative separation of the objects" (Gogel, as cited in Gogel & Mershon, 1969, p. 13). The adjacency principle can successfully account for the changes in lightness as a function of adjacency (i.e. displacement) in both fronto-parallel and depth plane and has shown to accurately predict the change of lightness for both actual and perceived displacements (Mershon, 1972).

Gogel's adjacency principle can also explain the effect of stereoscopic manipulation on the strength of the Koffka-Benussi ring illusion obtained by Wist and Susen (1973). When a homogenous gray ring is superimposed on adjacent black and white backgrounds so that one half of the ring is lying on the white and the other half on the black background, it appears homogenous. But, when a line is added, bisecting the ring along the black and white boundary between the two backgrounds, then the half of

[10] Although Wist and Susen, for example, consider the adjacency principle "more parsimonious" and also "more general…because it can make predictions about other perceived characteristics of the object" (Wist & Susan, 1973, p. 11), for example size (Gogel, 1965).

the ring seen against the black background appears lighter and the half seen against the white background appears darker, like in the simultaneous contrast illusion. The perceived lightness difference between the two halves of the ring significantly decreased when the bisecting line appeared either behind or in front of the display. Although the decrease of the difference didn’t reach the minimal level found when the display is presented without the line, the significant change in perceived lightness with no change in the retinal image suggests that retinal mechanisms are not sufficient to explain this illusion.

Wist (1974) also showed that perceived depth could modulate the strength of Mach bands, traditionally explained in terms of retinal lateral inhibition processes, but not the Herman grid illusion, which seems to be mediated by a different mechanisms than the illusions affected by variations in the perceived depth of their elements (Wist, 1974).

Coren (1969) stereoscopically varied the perceived depth of the elements in the Benary cross illusion and found that the illusion is reduced when the gray test triangles and the black inducing cross appeared in front of the white background, instead of coplanar with it. When only the cross appeared in a near depth plane, while the test triangles appeared coplanar with the white background, the illusion completely disappeared. This also suggests that lightness depended on the luminance relations within a plane. When perceived to lie in the same plane with the black cross (in front of the white background), target lightness increased; however, when perceived to lie in the plane of the white background target lightness decreased, although the retinal image remained constant across all conditions. However, the change in lightness with the change in perceived depth was again very small (0.25 - 0.33 Munsell units across different conditions).

Coren together with Komoda (1973), also showed the effect of perceived depth on lightness using a reversible figure of a tube whose perceived orientation spontaneously changed. Across reversals, the side of the tube that appeared to face outside always appeared significantly darker then the side that appeared to face inside. The authors interpretation is consistent with the inferential theory: the visual system relies on the assumption that the illumination level is always higher on the outside than on the inside of the object, so to account for the same luminance under lower illumination level, the reflectance of the inner side of the tube must be higher (Coren & Komoda, 1973)

Contrary to the findings in the previous studies, several authors reported failures to find the effect of depth on the classic simultaneous lightness contrast illusion (SLC). Julesz (1971) created a stereoscopic version of SLC using his famous random-dot stereograms and showed that the size of the illusion does not change when the gray test squares are perceived as floating in front of their inducing white and black backgrounds. Similarly, Gibbs and Lawson (1974) found no change in size of the SLC when the targets were seen either behind, in front of or coplanar to the inducing fields in the classic stereoscope presentation.

In summary, the results of the stereoscopic studies on the effects of depth on lightness are similar to those obtained in variations of Hochberg and Beck paradigm: the effects are very small (in average about half a Munsell step), sometimes, probably, too small to be recorded. However, Helmholzian explanation relying on cues to illumination, commonly used to account for the result of the studies inspired by Hochberg and Beck can not apply in the majority of stereoscopic studies, because no cues to the illumination were present in the stimuli.

The depth effect, although a small one, reported across wide variety of studies, indicates that depth does have some effect on lightness, although the nature of the mechanism mediating this effect is not clear. Further understanding of the underlying mechanism would require exploration of factors that could modulate the obtained depth effect. However, given that the effect was so small initially, registering the changes in effect size, as a consequence of manipulation of potentially relevant factors, would be quite difficult to register.

3. Gilchrist's coplanar ratio principle and some considerations

Using similar experimental logic as Hochberg and Beck, Gilchrist (1977, 1980) conducted experiments in which, contrary to the previous work, he obtained dramatic changes in lightness, nearly from white to black, with the change in perceived depth.

In one of the studies, the experimental setup consisted of two parallel planes that appeared like walls of two rooms connected by a doorway, a rectangular aperture in the near plane (back wall of "the front room"), through which one could see the far plane (back wall of "the back room"). While the front room was dimly illuminated, the back room was brightly illuminated by a hidden light source. A white paper square (the target) was attached to the side of the doorway in the near plane, in a position in which it was retinally adjacent to two surfaces belonging to two different depth planes: a black square in the dimly illuminated near plane and a white square in the brightly illuminated far plane. The perceived position of the target square was varied using false interposition cues. Without these, the target was perceived veridically, lying in the near plane. But, when notches were cut out of two corners of the target square, viewed monocularly, the square appeared as coplanar to the white square in the far plane and partially occluded by it. The target lightness changed dramatically with this change in perceived depth. In the near plane, coplanar to the dimly illuminated black square, the target appeared white (median observer match Munsell 9.0). In contrast, when perceived in the far plane, coplanar to the brightly illuminated white square it appeared dark gray (median observer match Munsell 3.5). Thus, virtually the same retinal layout yielded strikingly different judgments of target lightness, depending on the perceived depth.

In another study, Gilchrist (1977, 1980) used an experimental setup in which the display consisted of two perpendicular planes. One side of the display was horizontal, covered with white paper and facing upwards, while another side of the display was vertical, covered with black paper and facing the observer. A hidden light source was used to additionally illuminate the white side, while the black side was in dim illumination. Two equiluminant trapezoidal targets extended from the corner at which the two sides of the display met: a dimly illuminated white target extended from the black side and was seen against the brightly illuminated white side of the display, while a brightly illuminated black target, extended from the white side and was seen against the dimly illuminated black side of the display.

When observers viewed the display binocularly, the targets were seen veridically: the black target appeared coplanar with the brightly illuminated white side of the display and it was seen as black (median observer match Munsell 3.0). The white target appeared coplanar with the dimly illuminated black side of the display and it was seen as almost white (median observer match Munsell 8.0).

However, because the sides of the trapezoidal targets were trimmed, so that when viewed through a pinhole they matched the linear perspective projection of a rectangle lying on the side of the display that formed target primary retinal background, when the display was viewed monocularly, the perceived position of the targets changed: the brightly illuminated black target was now seen as coplanar with the dimly illuminated black background while the dimly illuminated white target, now appeared coplanar with the brightly illuminated white background. As in the parallel planes experiment, the change in perceived position was followed by a dramatic change in perceived lightness: the brightly illuminated black target now appeared almost white (median match Munsell 7.75) while the dimly illuminated white target appeared close to black (median match Munsell 3.75).

Note that the perpendicular planes experiment represents a critical test between two ratio hypotheses: the retinal ratio hypothesis, implicit in Wallach ratio principle stating that lightness depends on the luminance ratio of the target and its retinally adjacent neighbor, independent of the spatial arrangement, and the coplanar ratio hypothesis proposed by Gilchrist, which states that surface lightness depends on the luminance ratio between any target and its adjacent neighbor that is perceived to lie in the same plane (Gilchrist, 1980).

The results clearly support the coplanar ratio hypothesis: perceived target lightness dramatically changes when the perceived coplanar neighbor of the target changes, although the retinal ratios remain the same. Gilchrist's coplanar ratio principle is a modification of the Wallach ratio principle that takes depth into account: "Lightness depends on luminance ratios between adjacent retinal regions that appear to be coplanar"

(Gilchrist, 1980, 2006, p. 162). In a certain sense, in the coplanar ratio principle, Koffka's ideas get formalization, based on strong empirical evidence: "Two parts at the same apparent distance will, ceteris paribus, belong more closely together than the field parts organized in different planes", and "the more x [one field] belongs to y [the other] the more will its whiteness be determined by a gradient xy [ratio between them]" (Koffka, 1935, p. 246).

Gilchrist's experiments show not only that the perceived spatial arrangement can affect lightness – but that under certain conditions, a lightness value can shift from one to the other end of the whole range of grays, without any change in the retinal image. This result is inconsistent with the results of the studies described earlier in which depth effects are very modest and relatively unstable. Gilchrist's own experiments resulted from numerous trials, in which he, like his predecessors, failed to induce a significant depth effect on lightness (Gilchrist, 1980, 2006, for overview). Through the analysis of experimental conditions yielding a failure or a success he was able to formulate two critical conditions under which the perceived spatial arrangement had an effect on lightness that could be predicted by the coplanar ratio principle: (1) one was related to the possibility of perceptual (re)organization and (2) the other to the luminance range in the stimulus (Gilchrist, 1980).

(1) In all previous studies that failed to obtain large depth effects on lightness, the stimulus arrangements were such that, in at least one of the depth conditions, the target surface was isolated in its depth plane, so there was no coplanar standard in relation to which its lightness could be computed. In the absence of a coplanar referent surface, lightness can be indeterminate. For example, when a homogenous surface (Ganzfeld) fills

the entire visual field, the surface itself is not perceived, but only fog (Metzger, as cited by Koffka, 1935). Alternatively, if other surfaces are present in the visual field, but none of them is coplanar to the target surface, target lightness could be, by default, determined based on the retinal ratios, as the Wallach ratio principle suggests (Gilchrist, 1980). A similar account was proposed by Kardos in his principle of the next deeper depth plane, according to which the lightness of the surface that is isolated within its depth plane will be determined in relation to the surface(s) in the next nearest depth plane[11] (Kardos, 1934).

According to Gilchrist (1980), for the coplanar ratio principle to apply, the surface always needs to be grouped with other surfaces within its plane, and a change in perceived depth will produce a change in lightness only when the adjacent coplanar luminance, relative to which the surface lightness is computed, is different in the different depth planes. In other words, the shift in lightness obtained in Gilchrist's experiments occurred because the group of surfaces (i.e. plane) to which the target surface belonged changed across conditions and so did the luminance ratio that determined the lightness computation.

Gilchrist (1980) himself conducted experiments in which he failed to get the effects on lightness using a simplified version of the perpendicular planes display in which the stimulus consisted of only two perpendicular planes different in luminance. Perceived lightness did not change when the two planes appeared coplanar when seen monocularly, but perpendicular to each other (each isolated in its own plane) when seen binocularly.

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[11] "Surfaces that are not located in the plane of the actually present surface systems belong into the illumination sphere of the next deeper system." (Kardos, 1934 p. 57)

(2) The second condition necessary for the coplanar ratio principle to apply is photometric. Gilchrist noticed that large depth effects are obtained only when the luminance range within the image was large, approximately 900:1. The purpose of this constraint may be to limit the applicability of coplanar lightness computation only to situations in which it is likely to yield accurate lightness values. Note that, without the luminance range constraint, the coplanar ratio principle would predict that, any change in the luminance of the target's adjacent and coplanar neighbor as the target moves from one plane to another, will cause a change in target lightness, even if the illumination across planes is uniform. This is similar to the erroneous prediction of Wallach ratio principle that a surface of constant luminance will always change in lightness when it is seen against different backgrounds.

When the luminance range within an image does not exceed 30:1, any variation in luminance may be entirely attributed to differences in reflectance. In this case, the difference in luminance between different planes would be interpreted as a difference in reflectance and not a change in illumination. This is supported by results from Gilchrist's simple pilot perpendicular planes experiment, in which he failed to obtain a depth effect on lightness when the luminance ratio between planes (and within the image) was 30:1: the luminance difference between planes was always perceived as the reflectance difference, thus the lightness of each plane didn't change across conditions (Gilchrist, 1980).

However, if the planes in the image are differently illuminated, the coplanar ratio principle will accurately predict the change in lightness. A luminance range significantly larger than 30:1, may be a signal for the visual system that there are multiple fields of illumination in the scene. In such a case, the system tends to minimize the error in lightness computation by determining surface lightness within a plane because surfaces that lie in the same plane are usually equally illuminated. The hypothesis that the luminance range in the image serves to inform about the number of fields of illumination in the scene is in agreement with the theoretical principle of minimal number of light sources, proposed by Bergström (1994). If the visual system tends to account for luminance variation in an image, assuming a minimal number of light sources, then when the luminance range is 30:1, it will tend to attribute all luminance variation to reflectance while accounting for the larger range, such as 900:1 requires multiple fields of illumination.

Finally, one important methodological characteristic distinguishes the Gilchrist studies from the previous ones: Gilchrist used a between-subjects design, while all other studies used a within-subjects design. Gilchrist noted a significant effect of experience in the pilot studies he conducted:[12] the effect he obtained in within-subject pilot studies was exactly half a size of that obtained using two separate groups of observers. Both Gogel and Mershon (1969) and Coren (1969) reported that the order of presentation in their studies reduced the effect. Studies that involve manipulation of the perceived (and not the actual) change in the experimental settings are particularly sensitive in this regard because any "persistence" of the previous percept can significantly weaken or nullify the effect. Therefore, a between-subjects design provides a better assessment of the effect of perceived spatial arrangement on lightness.

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[12] "The tendency to see the targets as coplanar under monocular viewing seemed to persist into binocular presentation" (Gilchrist, 1980 p. 529).

Gilchrist's experiments showing that perceived depth can have a significant effect on lightness gained a lot of attention in the field, inspiring many replications. Some of them supported and some of them challenged the coplanar ratio principle.

Schirillo, Reeves and Arend (1990) replicated the Gilchrist parallel planes study by simulating an equivalent scene on a CRT screen using a pair of stereo images. They found that the lightness of the target changes when it appears to move from one plane to the other, in the direction predicted by the coplanar ratio principle, but the size of this effect was approximately half of that Gilchrist obtained using real paper-and-illuminant experimental setup. In the Schirillo et al. (1990) study, when the luminance range within a stimulus was 900:1, the target lightness changed from Munsell 5.25, when it appeared coplanar to the black paper in the near, dimly illuminated plane, to Munsell 3.25 when perceived coplanar to the white paper in the far, brightly illuminated plane. When the luminance range was 2000:1, similar to that used in Gilchrist's experiment the target lightness changed from Munsell 6 to 3.5 (an effect of 2.5 Munsell units, compared to Gilchrist's 5.5).

Interestingly, Schirillo et al. (1990) showed that only target lightness and not brightness (i.e. the perceived absolute amount of light a surface reflects) changed with the change in perceived depth. In a series of compelling illusions Adelson (1993), however, demonstrated that the perceived position in a three-dimensional configuration can also have an effect on target brightness, but hypothesized that the change in brightness is driven by the change in lightness.

Wishart et al. (1997) varied the degree of perceived slope in the Adelson's corrugated Mondrian illusion and showed that the bigger the perceived slope segregating planes within a configuration, the bigger the effect of perceived depth on brightness (and presumably lightness). This finding suggests that coplanarity is a graded variable, and not an all-or-none phenomenon: the more one plane is segregated in depth from the rest of configuration, the more the surface lightness will be determined in relation to other surfaces in that plane, rather than the rest of the visual field.

Note that both Gilchrist (1977, 1980) and Schirillo et al. (1990) obtained results that deviate from complete lightness constancy, strictly predicted by the coplanar ratio principle. In both the perpendicular and the parallel planes experiments, when the target was thirty times lighter than its perceived coplanar and adjacent neighbor, based on the coplanar ratio principle, it should appear white (Munsell 9.5). However, the obtained perceived values were significantly lower: Gilchrist (1977, 1980) obtained Munsell 8.0 and 7.75 in the perpendicular planes and 9.0 in the parallel planes experiment, while Schirillo et al. (1990) obtained Munsell 6.0 and 5.25 in the parallel planes replication. By the same token, when the target was at least thirty times darker than its perceived coplanar and adjacent neighbor, based on coplanar ratios it should appear black (Munsell 2.0). The obtained perceived values were quite dark, but not black: Gilchrist (1977, 1980) obtained Munsell 3.5 in the parallel planes and Munsell 3.0 and 3.75 in the perpendicular planes experiment, while Schirillo et al. (1990) obtained similar values in their replication (Munsell 3.5 and 3.25).

Schirillo and Arend (1995) suggested that such incomplete constancy is due to the fact that target lightness is determined not only by coplanar ratios, but also by non-coplanar retinal ratios: the target coplanar to the dimly illuminated black surface, which is perceived against the non-coplanar brightly illuminated white surface, is darkened due to the local contrast, so it appeared off-white or light gray; the target coplanar to the brightly illuminated white surface is lightened by the local contrast with the dimly illuminated black surface it is seen against.

Schirillo and Arend (1995) tested this hypothesis by comparing the target lightness when it was either completely or only partially surrounded by its coplanar neighbor. In the partial surround condition, as in the original experiments, the target was retinally adjacent to (though not coplanar with) either thirty times lower or thirty times higher luminance. They found that "lightness constancy is nearly perfect" (Schirillo & Arend, 1995, p. 229) when the target is completely surrounded by its coplanar neighbor. Interestingly, even the lightness matches in the partial surround condition were much closer to complete constancy than those obtained by Schirillo et al. (1990) in the comparable condition of the original study (Munsell 8.0 and 7.5 for the target thirty times brighter than its adjacent coplanar neighbor, compared to Munsell 6.0 and 5.25 of Schirillo et al.; also: Munsell 2.5 for the target thirty times darker than its adjacent coplanar neighbor compared to Munsell 3.25 and 3.5 of Schirillo et al.). One possible explanation of this result is that the planes in Schirillo and Arend study (1995) experiment were not homogenous as in the previous study (Schirillo et al., 1990), but articulated, consisting of numerous patches of different reflectance. Although it is well known that when there are multiple fields of illumination in a scene, stimulus articulation can increase constancy (Katz, 1935; Gilchrist & Annan, 2002), the depth effect obtained by Schirillo and Arend (1995) is very similar in size to that Gilchrist (1977, 1980) obtained when the display was poorly articulated. Thus, even if articulation enhances constancy and consequently the depth effect, it can not account for the difference in size of the depth effect obtained by Gilchrist (1977, 1980) and Schirillo et al. (1990), however, it inspires the question of whether Gilchrist would have obtained the stronger depth effect had he used articulated displays.

Numerous authors challenged the coplanar ratio principle. Marr (1982) reported that he could not replicate Gilchrist study, but did not publish the specific conditions under which the replication failed. Frisby (1979) published the same claim, but supported it by printing stero-images on paper, reducing the luminance range to 30:1 (Gilchrist, 2006).

Another challenge for the coplanar ratio principle comes from Zaidi, Spehar and Shy (1997), who showed that grouping based on T-junctions can override grouping based on the coplanarity for the purpose of lightness computation. Two main differences between the Zaidi et al. (1997) and Gilchrist (1977, 1980) studies may account for this result. (1) Stimuli Zaidi et al. used were 2-dimensional images presented on a CRT screen, in which depth is depicted only using pictorial depth information, and not binocular disparity; this might not have been strong enough depth cue to induce the depth effect on lightness. (2) The luminance range Zaidi et al. used was substantially smaller than that of used by Gilchrist (82:1 vs. 900:1). When Gilchrist and his collaborators (1998) replicated Zaidi et al. study using real objects in depth, but the same limited range, they obtained results like those of Zaidi et al., but when they expanded the luminance range to 900:1 they obtained results that supported the coplanar ratio principle (Gilchrist et al., 1998; Gilchrist, 2006).

Howe (2006) conducted a series of experiments testing the coplanar ratio principle, also using disparate stereo-images presented on CRT in which, depending on the condition, the luminance range varied from 61:1 to 236:1. He showed that the perceived lightness of a middle gray square target changes with the change in perceived depth only when the change in depth is associated with a change in perceived illumination. When the target moved from the plane of a white oblong to the plane of a dark gray-and-white checkerboard, it increased in lightness about 1 Munsell step, but only when in the checkerboard plane it appeared to lie in a shadow and not outside of it, even though the luminance relations were the same in both shadow and non-shadow conditions. Howe concluded that “the perceived illumination differences influence target lightness more than do coplanar relationships” (Howe, 2006, p. 299).

In a similarly designed study Dalby et al. (1995) also failed to obtain the depth effect on lightness predicted by the coplanar ratio principle, but using a luminance range as small as 1.2:1.

Finally, in a recent study, Maloney, Doerschner and Brainard (2007) reported that they failed to find evidence for the coplanar ratio principle in the domain of color.

Two main questions follow from this overview: (1) why, in the studies that did find the depth effect on lightness, is that effect so much smaller than the one Gilchrist obtained (Schirillo et al., 1990; Howe, 2006); and (2) why did other studies completely fail to find the effect of depth on lightness?

(1) Regarding the problem of the reduced size of the depth effect, several important methodological differences between the two groups of studies may account for this difference.

(a) While Schirillo et al. (1990) and Howe (2006) used a within-subjects design, Gilchrist used a between-subjects experimental design. As Gilchrist (1980) reported, when the observers serve as their own control the depth effect is significantly reduced.

(b) While Gilchrist (1977, 1980) used a real paper-and-illuminant three-dimensional scene, in the Schirillo et al. (1990) and Howe (2006) studies the depth was simulated, relying solely on stereo cues i.e. binocular disparity. It is possible that a real scene, which contains multiple interacting depth cues creates a stronger impression of depth, yielding a stronger effect on lightness when the perceived depth is manipulated.

The systematic differences between lightness experiments using computer simulation and those using real paper-and-illuminant displays have still not been systematically explored. However, it is possible that real paper-and-illuminant displays contain information about the surfaces and illumination (microtexture, gradients, etc) that are, unless intentionally modeled, artificially eliminated in the computer displays. The major advantage of using computer displays is the possibility to precisely control different parameters in the scene, but as a result, surfaces presented on the computer screen may be *too* homogenous and many subtle illumination gradients may be eliminated.

(2) Regarding failures to obtain a depth effect at all, these may be related to the luminance range constraint: when the luminance range in the stimulus is not big enough, the coplanar ratio principle does not apply. However, a problem in evaluating this claim is that the luminance range constraint is not specified well enough: in most of the failed replications the luminance range was larger than 30:1, but much smaller than the 900:1 range Gilchrist used.

Another problem may be treating the luminance range on a CRT screen and in real, paper-and-illuminant displays equivalently. While in the real displays, due to material imperfections, the maximal reflectance range between a black and a white is 30:1, this is not necessarily true for the computer displays. For example, if one draws a black square and a white square on a computer screen using any drawing program, the luminance range between these two squares can easily be 254:1,[13] yet the two squares will still appear as two simulated surfaces of different reflectance under uniform illumination. In the real depth scene, such a luminance range would be difficult to achieve with reflectance variation only. Also, it is difficult to imagine that the real scene containing a luminance range this large would appear uniformly illuminated. However, the hypothesis that the luminance range simulated on the computer monitor is processed differently than the same luminance range in the real scene requires further testing, and if correct, an explanation of which factors cause two photometrically equivalent stimuli to yield different percepts.

4. Anchoring theory of lightness perception

An important shortcoming of the coplanar ratio principle is that, like Wallach ratio principle, it provides the basis for computing only relative, but not absolute lightness values. To predict absolute lightness, the coplanar ratio principle needs to specify how the luminance ratios are mapped onto the lightness scale. In other words, it requires an anchoring rule. The anchoring problem is the core concept of a lightness theory developed by Gilchrist et al. (1999) aiming to provide a comprehensive account of lightness computation in both simple and complex images.

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[13] This ratio was obtained in an ad hoc measurement of a black and a white square drawn in program Canvas 9 and presented on a LaCie III electron monitor.

Unlike other theories that focus on how the visual system achieves a more or less veridical representation of object reflectance, the anchoring theory focuses on the pattern of lightness errors the system makes. Here the concept of error includes both failures of constancy and the traditional concept of illusion. The idea that visual illusions, apart from being wonderfully amusing demonstrations of imperfection of our visual system, have important heuristic value is relatively old among the vision scholars. Because the common goal of all theories is to explain how veridical perception is achieved, they all tend to make the same prediction about the final output of the computation. Thus, veridical perception cannot always distinguish between the theories. Illusions, on the other hand, can be thought of as ready-made tests for theories of vision (Gillam, 1998).

As Gilchrist (2006) points out, there is an incredible variety of lightness illusions and they are not merely random errors: under certain conditions, the visual system systematically fails to perceive lightness accurately.[14] Given that "both veridical and illusory percepts are the result of the same lawful processes" (Rock, 1984, p. 154), this pattern of errors can be understood as "a signature of the visual system" (Gilchrist et al., 1999, p.797).

Gilchrist et al. (1999) identify two main classes of illegitimate[15] lightness errors: (1) illumination dependent errors, caused by differences in illumination and (2) background dependent errors, caused by differences in reflectance of the background and

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[14] The concept of error is included in the very definition of the term constancy: "Perceived lightness of the surface remains roughly [not absolutely!] constant even though the illumination, and the luminance of the surface changes" (Gilchrist, 2006, p.7); "Constancy is phenomenal regression (or approximation) from the stimulus color to the real object" (Woodworth, 1934 interpreting Thouless, p.597)…and "apparent color is usually between these two poles" (Brunswick, as cited in Woodworth, 1934, p.597).

[15] Gilchrist (2006) distinguishes between legitimate errors, that occur due to lack of information and would be made even by the ideal observer and illegitimate errors, that occur when there is enough information contained in the stimulus, but lightness is still misperceived. Clearly, only illegitimate errors provide useful information about the mechanism of lightness computation.

argue that a successful theory of lightness needs to account for veridical perception, as well as for both types of lightness errors (Gilchrist et al., 1999; Gilchrist, 2006).

4. 1. Anchoring theory: Lightness computation in simple images

According to the anchoring theory, the visual system segregates an image into frameworks, which are functional units for lightness computation; thus to explain lightness perception requires description of the principles of computation within a framework. Anchoring theory first explores principles of lightness computation in simple images, i.e. images that contain at least two surfaces of different shade of gray that fill the entire visual field, but not more than a single framework (Gilchrist, 2006).

Gilchrist et al. (1999) note that relative luminance, although invariant with a change of illumination is also ambiguous. Namely, the relative luminance values can signify only how many times one surface is lighter or darker than another, but not the specific value of each surface on the lightness scale. To obtain the absolute lightness value for any surface, an anchoring rule relating the luminance ratios in the image to the scale of perceived grays, is necessary (Gilchrist et al., 1999; Gilchrist, 2006).

Several anchoring rules were proposed in the literature, but were not systematically tested. Wallach (1948), Land and McCann (1971), Horn (1986) and Marr (1982) proposed a highest luminance rule according to which the visual system assigns the value of white to the highest luminance in the visual field and scales the other values proportionally. Helson (1943, 1964) and Judd (1940) proposed an average luminance rule, in the chromatic domain also known as the gray world assumption (Buchsbaum, 1980; Hurlbert, 1986; Rubin & Richards, 1988), according to which the visual system assigns the value of middle gray to the average luminance in the visual field and scales other values relative to it. Finally, Kirschmann, (1892) and Rock (1983) proposed a bipolar anchoring rule – according to which the highest luminance in the visual field is assigned the value of white and the lowest luminance is assigned the value of black.

Li and Gilchrist (1999) tested the proposed anchoring rules by filling the observer's whole visual field with one simple image consisting of only two shades of gray. The observer's head was positioned in the middle of a large acrylic hemispheric dome divided by a vertical boundary into two halves. One half was painted black (equivalent to Munsell 2.5) and the other half dark gray (equivalent to Munsell 5.5). The observer's task was to make lightness matches for both halves of the dome from immediate memory. The results clearly supported the highest luminance rule: the dark gray half was perceived as white (median match Munsell 9.5) while the black half was perceived as gray (median match Munsell 4.5). Thus the highest luminance rule was established as an anchoring principle in simple images: the highest luminance in the image is perceived as white and lower luminance values are scaled relative to this standard, as predicted by the Wallach ratio principle (Li & Gilchrist, 1999; Gilchrist et al., 1999; Gilchrist, 2006).

Further research (Gilchrist & Bonato, 1995; Li & Gilchrist, 1999) showed this photometric anchoring principle is not sufficient to predict lightness values in simple images, and that geometric relations also play a role. When the area of the darker surface is larger than that of the lighter, the darker surface increases significantly in lightness with an increase in its area. Gilchrist and Radonjić (in preparation, also Radonjić & Gilchrist, 2005) measured lightness in nine bipartite radially sectored domes in which the relative size of the dark sector was systematically varied, from 5° to 355°. They found that when the darker sector also had the largest area its lightness significantly increased, from Munsell 4.9 perceived reflectance when it was smaller or equal in area to the lighter, to Munsell 7.5 when it subtended 355° of the visual field. These results provide the basis for a geometric anchoring rule - the area rule, according to which the largest region in the visual field tends to appear white.

In a simple image, the same surface can be the highest luminance and the largest area; in such a case the two anchoring rules will both predict that the same surface should be assigned the value of white. However, when the darker surface has the largest area and the lighter surface has the highest luminance, both will tend to appear white, each based on a different anchoring rule. This will be reflected in a significant lightening of the darker surface, when it is equal or larger then the lighter. Interestingly, the area rule applies only when a single surface covers more then half of the visual field in a simple image (i.e. more then half of a single framework in a complex image). Gilchrist and Radonjić (2007) found that when the larger darker sector is parsed into a number of smaller sectors, so that the cumulative darker area is larger, but the area of each darker sector is smaller than half of the visual field, the darker surface does not change in lightness with the increase in area.

The third rule of lightness computation in simple images is the scale normalization rule, which describes how the visual system resolves the scaling problem, i.e. mapping of the physical range in the stimulus onto the perceived range on the lightness scale. The scaling problem can be understood as the problem of constancy of lightness intervals (Gilchrist et al., 1999), because it refers to the question whether an interval in physical luminance is mapped onto an equal interval on the lightness scale, as suggested by one of Koffka's invariance principles (Koffka, as cited in Gilchrist, 2006) There are several possible solutions to this problem: the luminance range in the stimulus can be larger, smaller or equal to the perceived range. Based on the results of an experiment by Gilchrist and Bonato (1995), who measured the perceived range in the simple disk/Ganzfeld stimulus when the luminance range in the stimulus was varied Gilchrist et al. (1999) propose a scale normalization rule according to which the perceived range tends to get normalized toward the range of 30:1, corresponding to the reflectance range from white to black. This means that if the physical luminance range in the stimulus is larger than 30:1, the perceived range will tend to compress and if the physical range is smaller than 30:1, the perceived range will be tend to expand towards the canonical range (Gilchrist, 2006).

However, when Radonjić and Gilchrist (2005) directly tested the scale normalization rule, by systematically varying the physical range in dome displays they failed to find clear evidence for it: in some of the displays in which the luminance range was smaller than 30:1 the perceived range was compressed and not expanded. Clearly, the precise formulation of the scaling rule requires further testing.

4.2. Anchoring theory: Lightness computation in complex images

To explain lightness computation in complex images anchoring theory relies on the applicability assumption and the principle of co-determination. The applicability assumption means that, as complex images are segregated into frameworks, the rules of lightness computation found in simple images apply within frameworks of complex images.[16]

The principle of co-determination was proposed by Kardos (1934), who argued that the lightness of a surface is determined not only in relation to the field of illumination that a surface belongs to (called the relevant field), but also in relation to the adjacent field of illumination (called the foreign field). In other words, the lightness of a surface that belongs to a certain field of illumination is not independent from the structure and luminance distribution in the rest of the visual field. Theoretically, the co-determination principle establishes the role of the broader context in lightness computation. Practically, it offers a possible explanation for a wide variety of lightness errors.

Kardos's account and the anchoring theory, however, differ in their definition of the functional units for lightness computation and their organization within a complex image. According to Kardos, for the purposes of lightness computation, the image is segregated into fields of illumination and according to the anchoring theory into frameworks. Framework, a term originally conceived by the Gestaltists, has a broader meaning than field of illumination. It refers to "a group of surfaces that belong together, more-or-less" (Gilchrist et al., 1999, p. 804). A framework can thus be a group of surfaces in the same field of illumination, but also a group of surfaces that belong together based on some other grouping principle. The assumption that the image is segregated into frameworks and not simply fields of illumination is important because it

[16] For example, applicability of the area principle in complex images, has been supported by findings in at least a dozen of studies (Wallach, 1948; Stewart, 1959; Diamond, 1955; Stevens, 1967; Newson, 1958; Heinemann, 1955; Kozaki, 1963; Coren, 1969).

allows the concept of co-determination to account for not only illumination-dependent but also for background-dependent errors.

Kardos proposed that lightness is co-determined by relevant and foreign fields of illumination, while in the anchoring model lightness is co-determined by local and global frameworks. While the relevant and foreign fields of Kardos are mutually exclusive (the foreign field does not include the relevant field), local and global frameworks in the anchoring model are organized hierarchically: the global framework is superordinate, equivalent to the whole visual field and it includes multiple subordinate local frameworks. In a complex image, a target surface belongs to the global framework and either multiple hierarchically organized local frameworks progressively grouping towards the global framework, or to a local framework, which together with other adjacent, but not superordinate local frameworks groups into a global framework.[17]

If lightness is computed within the framework to which it belongs, then it is crucial to define what criteria determine the grouping of surfaces into frameworks. In other words: how are the frameworks within a complex image segregated? Kardos proposed two segregation factors: penumbra and depth boundaries. To these, the anchoring theory adds a number of weaker grouping/segregation factors that, based on the empirical evidence, influence lightness computation: the Gestalt grouping principles - proximity, similarity (Laurinen et al., 1997; Economou et al., 1998), good continuation (Economou et al., 1998), common fate (Agostini & Proffit, 1993; but see Howe, 2006), as well as different types of junctions – like X, T, Ψ junctions (Adelson, 1993; Anderson, 1997; Todorović, 1997; Zaidi et al., 1997), retinal proximity (Schirillo & Arend, 1995)

[17] Naturally, hierarchical and non-hierarchical organizations of local frameworks are not mutually exclusive. Within a global framework, one local framework may in hierarchical relation with some but not all local frameworks.

and luminance gradients, i.e. edge sharpness (Agostini & Galamonte, 1997). A framework within an image may be segregated based on a single or multiple segregating/grouping factors. For example, a group of surfaces that lie in the same plane can be segregated by a depth boundary, but the same group of surfaces may be also moving together in the same direction, so the segregation of this framework within a complex image will be supported by both a depth boundary and common fate.

According to the anchoring theory the lightness of a surface will be a weighted average of its lightness values computed within the local and within the global framework, based on the rules of lightness computation in simple images, now applied to frameworks within a complex image.[18] The weight of the values computed locally and globally will depend on the strength of the local framework relative to the global. According to the anchoring theory, the strength of the local framework depends on three factors: (1) its size, (2) its articulation, defined as the number of different elements within the framework and (3) the strength of its segregation from other parts of the image.

The importance of the first two factors was emphasized by Katz (1935). He provided substantial empirical evidence showing that the size[19] and articulation of a field of illumination (i.e. framework in terms of anchoring theory) increase lightness constancy: the bigger and the more articulated the field of illumination to which the surface belongs, the smaller the departure of the perceived from actual surface reflectance. The anchoring theory proposes a reinterpretation of Katz principles: the size

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[18] Theoretically, surface lightness is a weighted average of lightness computed within a global and within each local framework surface belongs to. However, for simplification, a model in which lightness is co-determined only by immediate local framework and the global framework will be used, while intermediate local frameworks will be disregarded.

[19] Although Katz gave equal weight to both perceived and retinal size, Cataliotti and Gilchrist (1995), Gilchrist and Bonato (1995) showed that lightness depends on the perceived and not retinal size (Gilchrist et al., 1999).

and the articulation of a framework per se, do not increase constancy specifically. Rather, they increase the strength of the local framework, thus the weight it has in the lightness computation. When a local lightness value is equivalent to the actual surface reflectance, field size and articulation do increase constancy. But they can also reduce it, when the local lightness value significantly differs from the actual reflectance.

Finally, the stronger a local framework is segregated within an image, the more weight it will have in lightness computation. A framework will be generally better segregated if it is supported by stronger factors (depth boundaries and penumbra), rather than weaker factors, or if it is supported by more, rather then fewer, grouping factors (Gilchrist et al., 1999).

Gilchrist et al. (1999) identify another factor that seems to influence framework strength. It is related to the insulation of a local framework within an image: a group of surfaces in a spotlight completely surrounded by a white border seems to create an extraordinary strong local framework, resistant to a large extent to the usual influences of the rest of the visual field (co-determination). The lightness of surfaces within such an insulated framework is almost entirely determined locally. Why a high-luminance border enhances the segregation and increases the framework strength so dramatically is not clear. The phenomenon cannot be explained based on local contrast: surrounding each member of a group with the same border doesn’t cause additional change in lightness. Also, the fact that it occurs only when the border is equal to the local highest luminance and not other luminance values adds further support to the idea that the highest luminance in a framework is treated as special by the visual system.

By relying on the principle of co-determination, anchoring theory can elegantly and parsimoniously account for a wide variety of lightness error. Generally, illumination-dependent errors occur because the global framework has too much weight in lightness computation: when multiple fields of illumination are present in the image, the lightness within a global framework will be equal to a luminance match and the lightness within a local framework will be equal to a lightness match. Thus, strengthening of the local framework will increase constancy, while strengthening of the global framework will decrease it. Background-dependent errors, however, occur because the local framework has too much weight in lightness computation: if there are not multiple fields of illumination within an image, global lightness will be equivalent to a lightness match, while local lightness, computed only within limited part of the visual field can significantly deviate from it. In this case, strengthening of the local framework will decrease and strengthening of the global framework will increase constancy.

5. Coplanar ratio principle in the light of the anchoring theory

The results of the Gilchrist (1977, 1980) studies of the depth effect on lightness can be easily explained in terms of the anchoring theory: the target lightness changes with the change of perceived depth because the perceived local framework to which the target belongs changes. As the two local frameworks have different highest luminance, the local lightness value, and consequently the perceived target lightness will be different across conditions. The perpendicular planes display consists of two subordinate frameworks segregated by a depth boundary; each plane represents one local framework, while the whole visual field including the display and the homogenous middle gray background represents the global framework. Given that the highest luminance in the visual field does not change across conditions, the global lightness values, unlike the local, will remain the same and equal for both equiluminant targets across conditions.

Within each local framework, the lightness of the target is computed according to the anchoring rules. In the binocular condition, the brightly illuminated black target is locally grouped with its coplanar brightly illuminated white background; given that it is thirty times lower in luminance than the highest luminance in that framework (plane), according to the highest luminance rule, it will locally be assigned the value of black. In the monocular condition, the local framework to which the target appeared to belong changes and so does its local lightness computation: it is perceived coplanar to the dimly illuminated black background and as it is now the highest luminance in that local framework, locally it is assigned the value of white. Theoretically, this change in lightness from locally black to locally white, should be reflected in a significant lightening of this target in the monocular condition; this prediction is supported by the data: the brightly illuminated black target lightened from Munsell 3.0 in the binocular to Munsell 7.75 in the monocular condition. The effect goes in the opposite direction for the dimly illuminated white target, which changes from Munsell 8.0 in the binocular to Munsell 3.75 in the monocular condition.

Note that the area rule should not affect the lightness of the target coplanar to illuminated white background, which is both the highest luminance and has the largest area. The two anchoring rules (highest luminance and largest area) give the same prediction. The area rule would apply in the plane that contains the shadowed black background, causing a lightening of the background, which has the largest area. However, it should not affect the target lightness, which, being the highest luminance will always be perceived as white (Gilchrist & Radonjić, in preparation). The scale normalization rule should also not apply in this case: given that the luminance range within each plane is 30:1, the theory predicts a 1:1 mapping of the physical range onto the perceived range.

Interestingly, anchoring theory can accommodate the results obtained by Gilchrist (1977, 1980) better than the coplanar ratio principle. If the coplanar ratio principle would strictly apply, one would expect the target lightness to change from black, when it appeared coplanar to the surface thirty times higher in luminance, to white, when it appeared coplanar to the surface thirty times lower in luminance. However, neither of the targets appeared totally black (equivalent to Munsell 2 or 2.5) nor totally white (equivalent to Munsell 9 or 9.5) in either of the conditions. This is predicted based on the anchoring theory principle of co-determination. Globally, each target has the same value regardless of planarity and this dilutes the effect of the local frameworks. In other words, factoring in these global values accounts for the shortfall in the depth effect (failure of constancy).

In its current version, anchoring theory is not able to clearly predict global lightness values because the exact scaling rule for the global framework has not been determined. That is, it is not known how the luminance range in the global framework is mapped onto the lightness range because the global luminance range is much larger than the range of the lightness scale. There are several obvious candidate rules. (1) One-to-one scaling. It is possible that all luminance values that are more than thirty times darker than the highest luminance are assigned the value of black. In the perpendicular planes experiment, the target is thirty times darker than the highest luminance in the global framework, so globally it would be assigned the value of black. Therefore, when the target is also thirty times darker than the highest luminance in the local framework, it should be perceived as black.

(2) Full normalization. Another possibility is that the range in the global framework is normalized to the 30:1 range of the lightness scale. In that case, the target is in the middle of the global range (on a log scale) and will be assigned the value of middle gray. This hypothesis seems to fit better with the data: the target that appears coplanar with the brightly illuminated white side of the display always appears dark gray (Munsell 3 and 3.75), which, although quite dark, is significantly lighter than black. Full normalization could also take one of two forms. The mapping could be linear between the minimum and maximum values, or it could be a sigmoidal function: compressed at both ends and more or less linear in the middle of the range.

In any case, the large lightness changes that Gilchrist (1977, 1980) obtained in his experiments suggest that the global framework is relatively weak relative to the local: the global lightness values remain constant across conditions, yet the target lightness changes dramatically.

6. Goals of the study

Inspired by empirical and theoretical contradictions in the literature on the effect of depth on lightness I designed a research program that revisits the question "when does perceived lightness depend on perceived spatial arrangement" (Gilchrist, 1980, p. 527). The goals of the research program were (1) to test the contradicting claims of the coplanar ratio principle and the anchoring theory about the mechanism visual system might use to determine lightness of a surface of the object in space; (2) test the coplanar ratio principle against some contradicting claims arisen in the recent literature and (3) to test specific conditions under which, according to the coplanar ratio principle, depth depends on lightness (Gilchrist, 1980).

In Experiment 1, I replicated the Gilchrist perpendicular planes experiment to establish a baseline measure of the depth effect on lightness.

In Experiment 2, I tested contradictory predictions of the coplanar ratio principle and the anchoring theory about the role of articulation in the depth effect.

In Experiment 3, I tested contradictory predictions of the coplanar ratio principle and low level theories that emphasize the role of local contrast mechanisms, about the role of adjacent luminance in the depth effect.

In Experiment 4, I tested whether target lightness depends on the highest luminance in the plane or the highest luminance in the framework of illumination. This problem tests two anchoring theory hypotheses on lightness computation when the planes contain multiple fields of illumination and a claim by Howe (2006) that "inferred illumination differences influence a target's lightness more than coplanar relations" (Howe, 2006, p. 299).

In Experiment 5, I explore whether continuity within a plane is necessary for the coplanar lightness computation to apply, or mere coplanarity is sufficient. In the second part of Experiment 5 (5A) I tested a claim of Kardos (1934) that surroundedness can substitute for continuity for the purpose of coplanar lightness computation.

Finally, in Experiment 6, I explored the role of luminance range on the depth effect on lightness, testing the specific prediction of the coplanar ratio principle, contrary to the prediction of the anchoring theory, that when the luminance range in the image is smaller than 30:1 depth does not have an effect on lightness.

II Experiments

To explore the factors modulating the effect of depth on lightness I used a version of Gilchrist's (1977, 1980) perpendicular planes display, an experimental set-up in which large depth effects on lightness perception are already well established. The perpendicular planes display was employed rather than the parallel planes display because of the following advantages. First, it permits one to change the perceived spatial position of the targets without making any change in the retinal image across conditions. Second, in the perpendicular planes display, the targets, which in the two conditions appear to belong to two different planes, also have different spatial orientations. According to the recently proposed *relaxed coplanar ratio principle*, surfaces facing the same direction may be compared for lightness even if they are not perceived to lie in the same plane (Gilchrist & Radonjić, 2006). To the extent that this hypothesis is correct, perceived changes in target lightness will be smaller when the targets are parallel and facing the same direction, as in the parallel planes display, than when they are perpendicular to one another, as in the perpendicular planes display. The perpendicular planes set-up, thus, maximizes the potential lightness difference between the two targets.

Experiment 1

Experiment 1 replicated Gilchrist's perpendicular planes experiment (1977, 1980) to establish the size of the depth effect that would be used as a baseline measure for further experiments.

I created a version of the perpendicular planes display consisting of two surfaces meeting at a right angle. One surface was covered with black paper and dimly illuminated; the other was covered with white paper and brightly illuminated. Two trapezoidal equiluminant targets extended from the corner at which the surfaces met: a white target (the lower target) extended from the lower half of the shadowed black side of the display and was seen against the lighted white side of the display, while a black target (the upper target) extended from the upper part of the lighted white side of the display and was seen against the shadowed black side of the display,

When viewed binocularly, the display was perceived veridically in depth: the targets appeared coplanar with the sides of the display they were extending from. However, when viewed monocularly each target, because it was trimmed to match the linear perspective projection of a rectangle lying on the side of the display it was seen against, appeared coplanar with that side: the lower target appeared as lying on the lighted white side of the display, while the upper target appeared as lying on the shadowed black side of the display. Thus, depending on viewing conditions (monocular or binocular) each target could be perceived in two different spatial positions, with different coplanar neighbors. Given that the luminance range in the display was 900 : 1, the coplanar ratio principle predicted that target lightness would change as a function of the perceived adjacent coplanar luminance.

This experimental design allows measuring of the depth effect, defined as the change in target lightness as a function of perceived adjacent coplanar luminance, in two ways: between-condition and within-condition. The between-condition depth effect can be computed for each target separately. It is equivalent to the difference in target lightness when the target appears coplanar with one adjacent luminance (i.e. side of the display) in one condition and another adjacent luminance in the other condition. Because the two targets in our experiment are equal in luminance, it is also possible to compute a within-condition depth effect; it is equivalent to the difference in perceived lightness of the two equiluminant targets, which appear to belong to different planes, having different coplanar adjacent luminances. Whenever possible, across experiments, I will primarily rely on a between-condition depth effect. The between-condition depth effect is considered a more accurate measure because: (1) it is based on the illusory change in perceived position of the target, thus it allows one to isolate the effect of *perceived* coplanarity on target lightness while all other aspects of the experiment are held constant, (2) it compares a target with itself in the two conditions; thus any difference in lightness that is caused by any actual physical difference between two targets (possibly produced by some uncontrolled factors in the experimental setting such as dust specks, visibility of the micro texture, etc) is constant across conditions, (3) between-subject comparisons tend to yield the maximal depth effect (Gilchrist, 1980).

Method

Apparatus. The experimental setup was arranged in a vision tunnel (117 cm x 60 cm x 60 cm), supported by four legs and divided into a stimulus chamber (51 cm long) and an observer chamber (66 cm long). The observer sat in the observer chamber and viewed the experimental scene through either one or two apertures centered in the wall dividing the two chambers. In the binocular condition, observers viewed the display through two round apertures, each 3 cm in diameter. In the monocular condition, observers viewed the display through a pinhole (3 mm in diameter), centered within the right aperture, while an occluding panel covered the left aperture. The floor and the right sidewall of the tunnel were covered with gray paper (Color-aid 4.5, reflectance 24.6%)

while the other sidewall, the ceiling and the front wall were painted matte black. The back wall of the tunnel was covered with white matte paper (reflectance 90%).

Dihedral corner display. Looking through the aperture(s), the observer saw what appeared to be two sides of a large cube suspended in midair straight ahead (23.5 cm above the floor). The two visible sides of the "cube" met at a vertical right angle pointing towards the observer. Each side of the display was 11 cm on a side and constructed from Color-aid paper. The left side was black (black Color-aid paper, reflectance 3.1%), while the right side was white (white Color-aid paper, reflectance 90%). These paper sides were mounted on a support apparatus consisting of two square aluminum panels, which formed a dihedral corner, supported by an aluminum rod that extended 16 cm from the center of the far end of the tunnel and was occluded by the dihedral corner itself.

Two square paper targets, 4.5 cm long and approximately 4 cm high extended from the dihedral corner itself. The lower target was white (back side of a black Color-aid paper, reflectance 90%) and was attached to the bottom half of the black side of the display. The upper target was black (Color-aid black, reflectance 3.1%) and attached to the upper half of the white side of the display. Each target was bonded to a thin metal panel. The lower, white target extended from the black side and was seen against the white side of the display. The upper, black target extended from the white side and was seen against the black side of the display. In order to make targets appear as though they were lying flat on the sides of the display against which they were seen when viewed monocularly, the targets were cut in a trapezoidal shape so that when viewed from the pinhole position, the horizontal and vertical edges of the target appeared parallel to the horizontal and vertical edges of the display.

Illumination. The scene was illuminated by a 100 W incandescent bulb attached to the right wall of the stimulus chamber 30 cm away from the display. Occluded from the observer's view by an aluminum panel (16.5 cm high, 17.5 cm wide), the bulb directly illuminated the white side of the display (the lighted side) and the black target extending from it. The black side of the display (the shadowed side), and the white target extending from it were in a dim illumination. Facing away from the lighted side, they were not directly illuminated by the bulb. The illumination ratio between the two sides of the display was equal to the reflectance ratio between the white and black targets, approximately 30:1.

To achieve equiluminance of the brightly illuminated black target and the dimly illuminated white target, a piece of white paper was attached to a black panel (the reflecting panel) placed in the front left of the tunnel, parallel to the shadowed side of the display and out of the observer's view. By changing the size of the white paper, the amount of light reflected from the paper onto the white target could be manipulated and adjusted with good precision.

Proximal stimulus. At the viewing distance of 42 cm, the dihedral corner subtended 15° of visual angle vertically and 20.2° of visual angle horizontally. Each target subtended 6.2° of visual angle vertically and between 5.5° of visual angle and 4.8° of visual angle horizontally.

Photometric measurements were taken using a Konica Minolta LS-100 luminance meter. The luminance of the targets was 17.6 cd/m^2. The luminance of the shadowed black side of the display was 0.59 cd/m^2 and the luminance of the lighted white side of in the illumination of the display was 528 cd/m^2. The luminance range within the display, measured as the ratio between the black in the shadow (equivalent to the lowest luminance in the shadow), and the white on the illuminated side (equivalent to the highest luminance in the illuminated side), was 900:1. The luminance of the background wall varied from 525 cd/m^2 on the right side, and 242 cd/m^2 on the left side.

Matching chart. Matching was done using a Munsell chart, housed in a metal chamber mounted directly below (48 cm) the viewing slot and separately illuminated by a 15W fluorescent tube mounted 10 cm above the chart. The chart consisted of 16 chips, 1 cm x 3 cm each, mounted on the white background. The chips on the chart were arranged in ascending reflectance order: from black, equivalent to Munsell 2.0 to white, equivalent to Munsell 9.5, with 0.5 steps intervals. The luminance of the white chip was 360 cd/m^2.

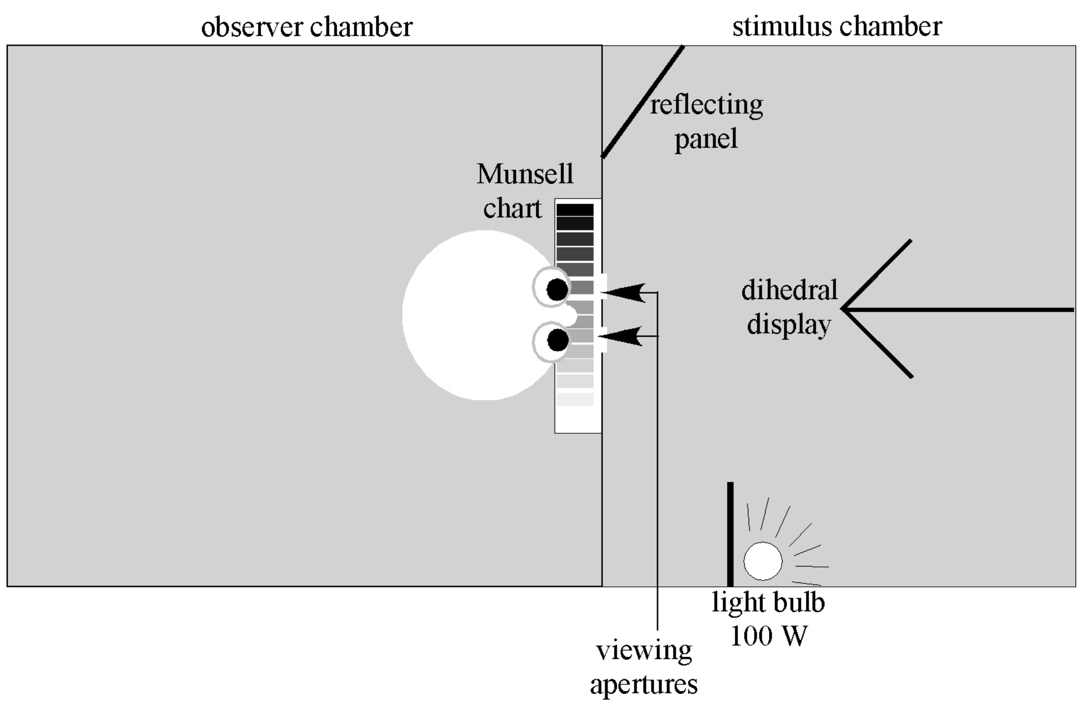

Figure 1: Plan view of the experimental apparatus (drawn to scale)

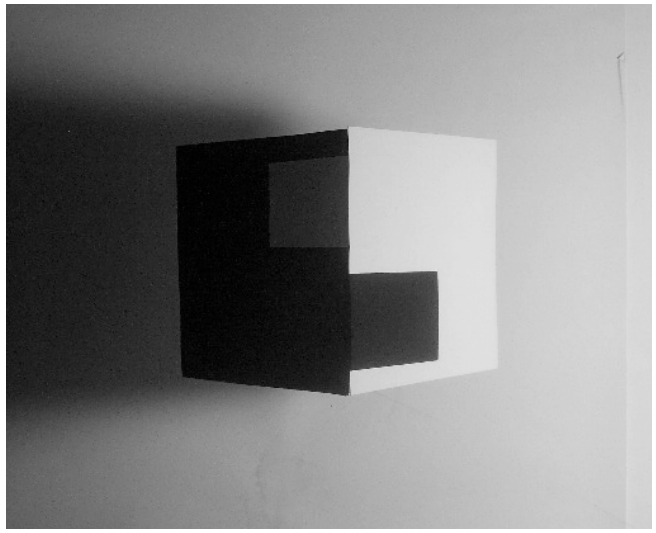

Figure 2: A photograph of the display from the observers' viewpoint

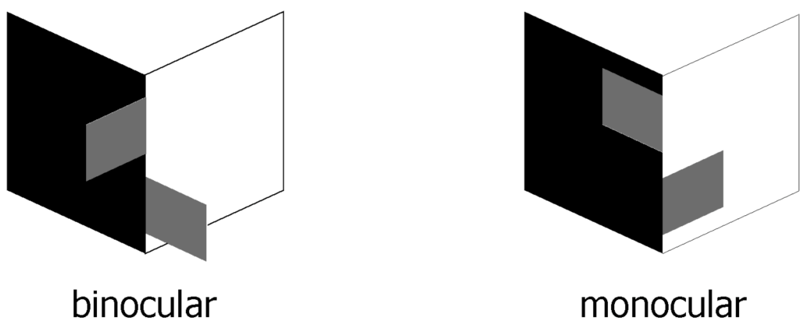

Figure 3: A perspective view that illustrates the perceived spatial arrangement (not the observer's retinal image) in the binocular and monocular conditions (actual target positions did not change).

Instructions. At the beginning of the experimental session each observer was given lengthy instructions, which included an explanation of the notions of lightness and brightness with concrete examples, introduction to the Munsell chart and explanation of their task in the experiment[20]. The observer was then asked to take a seat in the observer chamber and look into the tunnel though the aperture(s). In the binocular condition the

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[20]The full text of the instructions is given in Appendix 1.

observer was asked to look through two round openings, “like looking through binoculars”. In the monocular condition, the observer was asked to look through the pinhole “like peeking through a keyhole”.

The experimenter then asked the observer if he/she saw the display that looked like a corner of the cube, with one side darker and another side lighter and than asked questions to establish the perceived spatial position of the targets. In the binocular condition, the experimenter asked: ”Do you see two big squares extending from each of the sides of the cube; one is in the top position and the other is in the bottom position. Which one is extending towards me - the top or the bottom one? What about the other one?” In the monocular condition the experimenter asked: ”Do you see two big squares one on each side of the cube; one is in the top position and the other is in the bottom position. The one in the top position, on which side of the cube is it on, left or right? And the one in the bottom?”

After establishing the perceived position of the target, the observer was asked to match the lightness of each target i.e. ”to pick a chip from the chart that is the same actual color as the target; that is, cut from the same piece of paper as the target”. In the monocular condition, after making lightness judgments, the observer was asked if the targets appeared as if they were lying flat on the sides of the cube, to ensure the targets were perceived in their intended spatial position.

After this, the observer was debriefed (shown the actual setup and told the purpose of the experiment). The surprise of observers participating in the monocular condition after the actual position and reflectance of the targets was revealed to them was a further proof that the experimental manipulation of perceived position of the targets was successful.

Observers. A separate group of 20 observers matched the target lightness in each condition. In each condition, one half the observers first judged the lower target while the other half the observers first judged the upper target.

Criteria for exclusion. Three criteria for the exclusion of observer responses from the data analysis were applied throughout all experiments. The observer matches were excluded when (1) the observer failed to perceive the intended spatial position of the targets, (2) it was established (during debriefing session) that the observer was making brightness and not lightness matches (e.g. "I saw the target was white, but it appeared darker; I matched how it appeared.") (3) the observer matches fell more than 3 standard deviations above or below the mean of the whole group in a given condition.[21] Each excluded observer was replaced by a new observer so that valid data from 20 observers were collected in each condition.

Based on these exclusion criteria 4 observers were excluded (and replaced) from Experiment 1: three for making brightness instead of lightness matches and one for being an outlier. All four participated in the binocular condition.

Results

The mean lightness matches for each target in the monocular and binocular condition are shown in Figure 4.[22]

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[21]Excluding the match of the potential outlier(s).

[22]For the purpose of data analysis, all Munsell matches are converted into log reflectance. I will refer to Munsell values solely to provide additional orientation for readers more familiar with the Munsell scale. All statistical analyses are performed on matches converted in log reflectance.

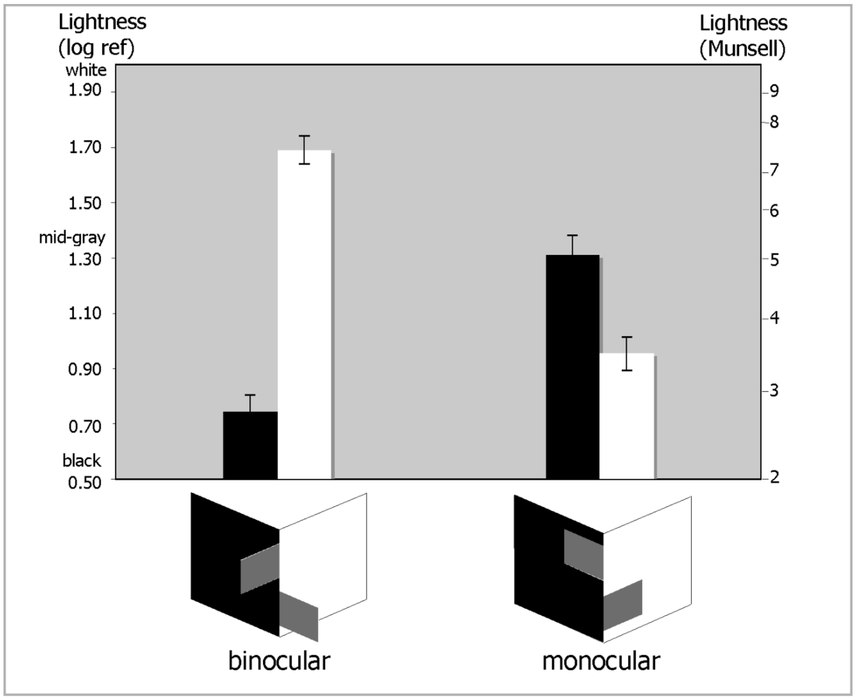

Figure 4: Experiment 1. Target lightness in the monocular and binocular conditions. Lightness of the upper, lighted black target shown in black. Lightness of the lower, shadowed white target shown in white.

A repeated measures analysis of variance (ANOVA) with condition (monocular vs. binocular) as a between-subjects factor and target (upper vs. lower) as a within-subjects factor revealed a significant main effect of target, $F(1,38) = 16.47$, $p < 0.001$. Overall, the upper (black) target was perceived as darker ($M = 1.03$, $SE = 0.06$) than the lower (white) target ($M = 1.32$, $SE = 0.07$). The ANOVA also revealed a Target x Condition interaction, $F(1, 38) = 81.11$, $p < 0.001$ (see Figure 4).

Planned comparisons further explored the interaction between target and condition. Paired *t*-tests revealed that the two equiluminant targets differed in lightness both within the binocular condition, $t(19) = 8.00$, $p < 0.001$ and within the monocular condition, $t(19) = 4.16$, $p = 0.001$. In both conditions, the target that appeared coplanar with the lighted side of the display (upper target in the binocular, and lower target in the monocular condition) was perceived as significantly darker than the target that appeared coplanar with the shadowed side of the display (lower target in binocular, and upper target in monocular condition).

Independent *t*-tests revealed that the perceived lightness of each target varied as a function of the plane to which the target was perceived to belong. The lower, white target appeared light gray (1.69 log reflectance, equivalent to Munsell 7.6) when perceived as coplanar with the shadowed side of the display in the binocular condition, but dark gray (0.95 log reflectance, equivalent to Munsell 3.6), when perceived as coplanar with the lighted side of the display in the monocular condition, $t(38) = 6.78$, $p < 0.001$. The upper, black target appeared nearly black (0.74 log reflectance, equivalent to Munsell 2.9), when perceived as coplanar with the lighted side of the display in the binocular condition. By contrast, it appeared middle gray (1.31 log reflectance, equivalent to Munsell 5.2) when perceived as coplanar with the shadowed side of the display in the monocular condition, $t(38) = 8.16$, $p < 0.001$.

Further, the size of the between-condition and within-condition depth-effect was computed. The between-condition depth effect yielded 0.74 log reflectance (equivalent to 4 Munsell units) for the lower target and 0.57 log reflectance (equivalent to 2.4 Munsell units) for the upper target. Although the change in lightness across conditions for the black target was smaller than for the white target, this difference failed to reach significance, $t(38) = 1.32$, $p = ns$.

The within-condition depth effect yielded 0.94 log reflectance (equivalent to 4.8 Munsell units) in the binocular condition and 0.35 log reflectance (equivalent to 1.6

Munsell units) in the monocular condition. The within-condition depth effect for the binocular condition was significantly larger than that in the monocular condition, $t(38) = 4.08$, $p < 0.001$.

Discussion

Both between-condition and within-condition target comparisons show a clear depth effect, as predicted by the coplanar ratio principle (and the anchoring theory). Within a condition, the two equiluminant targets that appeared coplanar with different adjacent luminance were perceived as different in lightness. In both binocular and monocular conditions, the target that appeared coplanar with the shadowed, black side of the display was perceived significantly lighter than the target that appeared coplanar with the lighted white side of the display.

Also, the perceived target lightness changed significantly when the perceived plane the target belonged to changed. The lower, white target appeared light gray when perceived as coplanar with the shadowed black side of the display in the binocular condition but appeared nearly black when perceived as coplanar with the lighted white side of the display in the monocular condition. The upper, black target appeared nearly black when perceived as coplanar with the lighted white side of the display in the binocular condition but middle gray when perceived as coplanar with the shadowed black side of the display in the monocular condition.

The results reveal an unexpected asymmetry: the depth effect was significantly larger in the binocular condition than in the monocular condition If target lightness depends on the luminance ratio between the target and its adjacent coplanar luminance only, as proposed by the coplanar ratio principle, then the magnitude of the depth effect in both binocular and monocular conditions should have been the same.

To explore this asymmetry in the within-condition depth effects, post-hoc *t*-tests comparing the two targets that across conditions appeared coplanar with the same luminance (side of the display) were conducted. The *t*-tests revealed that the target perceived to lie in the lighted plane in the monocular condition appeared lighter than the target perceived to lie in the lighted plane in the binocular condition, $t(38) = 2.44$; $p < 0.05$, and the target that appeared to lie in the shadowed plane in the monocular condition, appeared darker than the target that appeared to lie in the shadowed plane in the binocular condition, $t(38) = 4.30$; $p < 0.001$, even though the coplanar luminance relations were the same. In both comparisons, the difference went in the direction of the actual target reflectance. Interestingly, when obtained results are compared with those obtained by Gilchrist (1977, 1980) the same trend was found, though much less pronounced. [23]

Three possible reasons can be suggested for this monocular/binocular discrepancy.

(1) One reason may be uncontrolled visibility of flaws or specks of dust. A speck of dust on the surface of the black target in bright illumination would be easily visible and lighter than the target itself. This might be a sufficient cue to suggest that the target is a darker shade of gray. Despite the best efforts to keep the targets and the display clean,

[23] In the Gilchrist experiment, the within-condition depth effect was also smaller in the monocular than in the binocular condition (4 vs. 5 Munsell units). Also, the white target in the monocular condition was lighter than the black target in the binocular condition (Munsell 3.75 vs. Munsell 3) and the black target in the monocular condition was darker than the white target in the monocular condition (Munsell 8 vs. Munsell 7.75), despite the same coplanar luminance relations; however these differences were quite small and not significant.

there is always the possibility that due to uncontrollable factors, the targets were not spotless. Note that in the context of this experiment, such flaws would interfere with the perceived lightness only for the upper, black target viewed in the monocular condition, when it was intended to be perceived as the highest luminance in the local framework. This is consistent with the fact that that the biggest discrepancy of obtained lightness values from the expected ones based on the anchoring theory,[24] as well those obtained by Gilchrist (1977, 1980)[25] is obtained for the upper, black target in the monocular condition. The white target in the shadow is more resistant to the influence of specks than the black target, because the illumination is lower. Therefore, in monocular condition the lower, white target served as a control for the black one in estimating the depth effect on lightness.

(2) Another possibility is that the difference in lightness is a result of the observers' failure to see the targets in their intended spatial position in the monocular condition, which would then significantly affect the perceived target lightness. Although the data were discarded for any observers who saw the targets in the wrong depth plane, some observers reported minor deviations from the co-planarity for one or the other target that might have affected the perceived lightness. Such comments ("not completely flat, but coming out at one end" or "one side was lifted") were recorded occasionally, but equally often for both targets. These observer matches were not discarded because the positions of both targets were close to the intended positions.

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[24] In the monocular condition, this target is perceived as middle gray, not light gray as predicted by the anchoring theory.

[25] All other lightness values obtained in Experiment 1 are very similar to those obtained by Gilchrist. In the binocular condition: Munsell 7.6 for the lower, white and Munsell 2.9 for the upper, black target are close to Munsell 8 and Munsell 3, Gilchrist obtained for each target, respectively. In the monocular condition, matches for the white target are practically the same in Experiment 1 (Munsell 3.6) and in Gilchrist experiment (Munsell 3.75).

(3) Finally, it is possible that the difference in lightness of the target coplanar with the same adjacent luminance in the monocular and binocular condition occurred because in the binocular condition, the available depth cues enabled better perceptual segregation of the planes, thus stronger grouping of the target with its perceived depth plane. Both binocular disparity, in the binocular condition, and linear perspective, in the monocular condition are strong depth cues, and when pitted against each other in isolation can cause bi-stability of the perceived position of the object (van Ee et al., 2002). However, in a real 3D scene, as in this experiment, in the binocular condition, other depth cues, such as convergence, accommodation and motion parallax can provide information about the position of the targets in addition to binocular disparity and enhance the segregation. Indeed, one possible reason for the smaller depth effects obtained in the experiments discussed in the introduction in which the perceived depth is simulated on the CRT screen, may be manipulating only binocular disparity (Schirillo, Reeves & Arend, 1990; Howe, 2006). Real scenes typically contain richer depth cues, so manipulating the perceived depth in real displays may cause a bigger change in perceptual organization of the scene, and consequently a bigger depth effect.

According to the anchoring theory, better segregation increases the strength of the local framework. Therefore, if the existence of multiple depth cues in the binocular condition makes depth frameworks better segregated, this would imply that, in this condition, local lightness values would have more weight in the lightness computation than in the monocular condition.

Remember that anchoring theory predicts that the target perceived as coplanar with the shadowed side of the display should be perceived as light gray in both monocular and binocular conditions (locally white, globally nearly black). If due to better segregation, the local framework has more weight in the binocular condition, this target would appear lighter in the binocular than in the monocular condition and this is what is obtained (Munsell 7.6 vs. 5.2).

For the target perceived as coplanar with the lighted side of the display, anchoring theory predicts it would appear nearly black in both conditions (locally black, globally nearly black). Due to better segregation, this target should appear darker in the binocular than in the monocular condition. Again, that is what is obtained (Munsell 2.9 vs. 3.6 Munsell). Thus, for both targets, the magnitude of the change in lightness across conditions is consistent with the segregation hypothesis.

The anchoring theory also accounts for the fact that the size of the effect (the difference between conditions) is bigger for the target perceived as coplanar with the shadowed side of the display. This is due to the fact that the difference between global and local lightness values for this target is larger (locally white, globally nearly black) than for the target coplanar with the lighted side of the display (locally black, globally nearly black).

Experiment 2: Role of articulation in the effect of depth on lightness

Articulation is a term that has been extensively used in the context of lightness research, but has never been clearly defined (Gilchrist & Annan, 2002; Gilchrist, 2006).[26] It is generally used to describe the complexity of a stimulus, but this complexity can be manifold; it can refer to number of different shades of gray,[27] number of different surfaces or objects in the visual field,[28] number of different frameworks of illumination, or number of different depth planes (Henneman, 1935; Maloney & Schirillo, 2002).[29] Gilchrist & Radonjić (2007) have shown that when the luminance range is kept constant in a display with two or more regions of illumination, target lightness changes as a function of a number of surfaces within a stimulus, and not number of shades of gray, and this is how articulation will be defined in this research.

Katz (1935) was the first lightness scholar to emphasize the importance of articulation in lightness perception. He empirically demonstrated that increasing the number of elements in the display significantly improves lightness constancy. Greater constancy with greater articulation has been subsequently demonstrated by Burzlaff, Katona, and Henneman (as cited in Gilchrist, 2006). While in the non-articulated displays the degree of constancy expressed by Thouless ratio ranged from 35% to 65%, in richly articulated displays it increased to nearly perfect constancy (95% or even 100%). The same effect of articulation on lightness constancy has been demonstrated in some more

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[26]"Articulation...is a rather vague term in badly need of clearer definition and explanation." (Henneman, 1935)

[27]"…number of surfaces of different reflectivity." (Henneman, 1935)

[28]"…numerous objects readily distinguishable from each other"(Burzlaff), "…a variety of objects…" (MacLeod) "…more contours, more form and object characters…"(Katona, all as cited in Gilchrist, 2006).

[29]Articulation is sometimes also used to refer to "organization of the visual field" (Gelb, as cited in Gilchrist, 2006 and Woodworth, 1938); however this is very different from the common understanding of this term.

recent studies. Arend and Goldstein (1987) showed that articulation enhances constancy in CRT displays where changes of illumination were simulated. Schirillo & Arend (1995), in the experiment testing the role of local contrast in the effect of depth on lightness using articulated mondrian displays (described in the introduction) obtained greater constancy and a greater depth effect than in their initial replication of the Gilchrist parallel planes study (1977, 1980) using non-articulated displays (Schirillo et al., 1990).

Although it is empirically established that articulation is an important factor in lightness constancy, no theoretical explanation for this phenomenon had been proposed. Katz himself never integrated the concept of articulation into his theory of lightness. The hypothesis based on empirical findings, that articulation enhances the stability of perceived color and lightness of a surface, i.e. increases constancy, is also widespread today (Maloney & Schirillo, 2002). But, as Woodworth (1938) notes, “there is no suggestion why the effect [of articulation] should be in the direction of seeing the object color [lightness], rather than stimulus color [luminance]”.

There is evidence, however, that, contrary to Katz’s original understanding, in some conditions, articulation decreases constancy and increases the strength of lightness illusions. For example, when the backgrounds of the simultaneous contrast display are articulated, the perceived difference between two equiluminant targets is increased (Adelson, 2000; Gilchrist, 2006). By the same token, decreasing articulation significantly decreases the strength of the lightness illusion (increasing lightness constancy) in Adelson’s corrugated plaid illusion, (Wishart et al., 1997; Gilchrist et al., 1999), White’s illusion (Gilchrist & Annan, 2002) or reverse contrast illusion by Economou (Economou et al., 1998).

In an attempt to integrate these apparently contradictory findings, Gilchrist et al. (1999) propose an alternative explanation of articulation phenomenon in the context of the anchoring theory, according to which articulation is a factor contributing to the strength of the local framework. According to the anchoring theory, perceived lightness is equivalent to a weighted average of target lightness determined within a local and within a global framework. The relative weight of each framework depends on the framework strength, which is determined by factors such as field size, strength of segregation and articulation. According to the anchoring theory, articulation will have a differential effect on lightness constancy, depending on the type of grouping for lightness applied by the visual system in a given situation i.e. type of framework present in the stimulus.

In the case of illumination-independent constancy, when frameworks in the visual field are equivalent to fields of illumination, articulation will increase constancy, just as Katz observed, by reducing the illumination-dependent lightness errors. Such errors, as described in the introduction, occur because the global framework has too much weight in the lightness computation; thus increasing the articulation will strengthen the local framework and increase its weight in the computation.

However, in the case of background-independent constancy, when frameworks in the visual field are segregated by other grouping factors (for example, gestalt grouping principles) and there are no multiple fields of illumination within the image, articulation will decrease constancy, like in the examples of lightness illusions described above, by increasing background-dependent lightness errors. Such errors occur because the local framework has too much weight in the computation, and a further increase in articulation will increase further the weight a local framework has in the computation.

Thus, anchoring theory predicts that, by manipulating the articulation of a local framework, one should be able to change perceived target lightness by changing the weight that framework has in lightness computation.

Note that in Gilchrist's perpendicular planes experiment (1977, 1980) each side of the display consists of only two homogenous surfaces; in other words: the local frameworks are poorly articulated. Articulating the sides of the display should, according to the anchoring theory increase the weight of each local framework in lightness computation. Given that the difference in target lightness comes from the difference in local lightness values, articulation should increase the perceived lightness difference between the targets as well as the perceived change in lightness for each target with a change in perceived position.

Furthermore, the anchoring theory predicts that articulation will have a bigger effect on the target that is perceived coplanar with the shadowed side of the display than the target that is perceived coplanar with the lighted side of the display. This is because the articulation is held to influence the relative weighting of local and global lightness values and the target coplanar with the lighted side of display is assigned similar values both locally and globally, because both frameworks have the same highest luminance (white in bright illumination). For the target coplanar with the shadowed side of the display, there is a large difference between the highest luminance in the local and in the global framework, and thus a large difference between the locally and globally assigned lightness values. Locally, being the highest luminance in the framework, this target is assigned the value of white, while globally it is assigned a much darker value. Thus, the perceived lightness of this target should strongly depend on the articulation of its local, that is shadowed, framework. When the local framework is articulated this target should be perceived as significantly lighter.

From this analysis it follows that the articulation of the shadowed side of the display will have a bigger effect on coplanar target lightness, and consequently the depth effect, than the articulation of the lighted side of the display.

Note that the coplanar ratio principle, in its original formulation (Gilchrist, 1977, 1980), does not assume any critical role of articulation in lightness computation within a plane. Thus, it would not predict any difference in the size of the effect when the sides of the display are articulated, as long as the coplanar adjacent luminance is the same. In Experiment 1, we articulated both sides of the display to test whether articulation increases the depth effect on lightness, as predicted by the anchoring theory.

Method

Experiment 2 was identical to Experiment 1 in all respects except that each side (both the black and the white) side of the dihedral corner was replaced with a mondrian pattern, each consisting of 20 patches of different reflectance ranging from black to white. The structure of the pattern was pseudorandom and approximately the same for both sides. Only the white patch in the lighted side of the display and the black patch on shadowed side had a fixed and not a random position. To avoid changes in local contrast, the white patch on the lighted side was kept adjacent to both targets so that the their retinal surround remained the same as in Experiment 1. The position of the black patch on the shadowed side of the display was such that the most, but not all of the retinal surround of the targets remained the same as in Experiment 1: some patches lighter than black were adjacent to both targets. To minimize this change in average luminance, the retinal surround of the targets, and the effect it might have on target lightness, the reflectance of adjacent patches was kept relatively low. Note that any effect of this change, based to the local contrast, would be reflected in a darkening of the target perceived as coplanar with the shadowed side of the display. This is opposite of the articulation effect predicted by the anchoring theory; however, this potential confound will be taken into account in the data analysis.

The luminance of the target, the highest luminance in the lighted and the lowest luminance in the shadowed side of the display were all identical to Experiment 1. The highest luminance in the shadowed side of the display was 13 cd/m^2 and the lowest luminance on the lighted side of the display was equivalent to the target luminance.

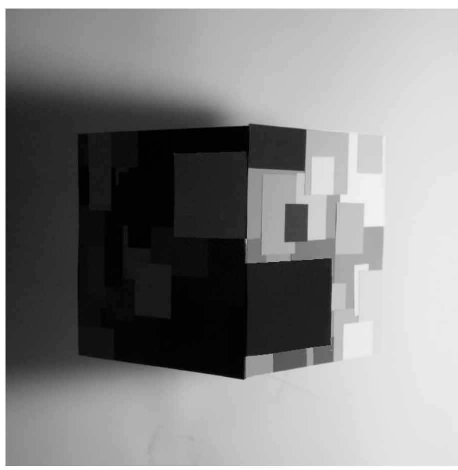

Figure 5: A photograph of the display with both sides articulated, from the observers' viewpoint.

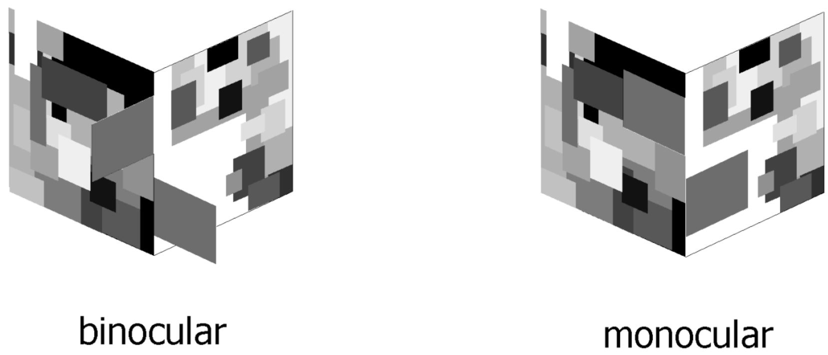

Figure 6: A perspective view that illustrates the perceived spatial arrangement (not the observers' retinal image) in the binocular and monocular conditions when both sides of the display were articulated (actual target positions did not change).

A separate group of 20 participants viewed the display in the monocular and binocular conditions. Based on the exclusion criteria two observers were excluded (and replaced), both from monocular condition, as they were identified as outliers.

Results

The mean lightness matches for each target in the monocular and binocular conditions are plotted in Figure 7.

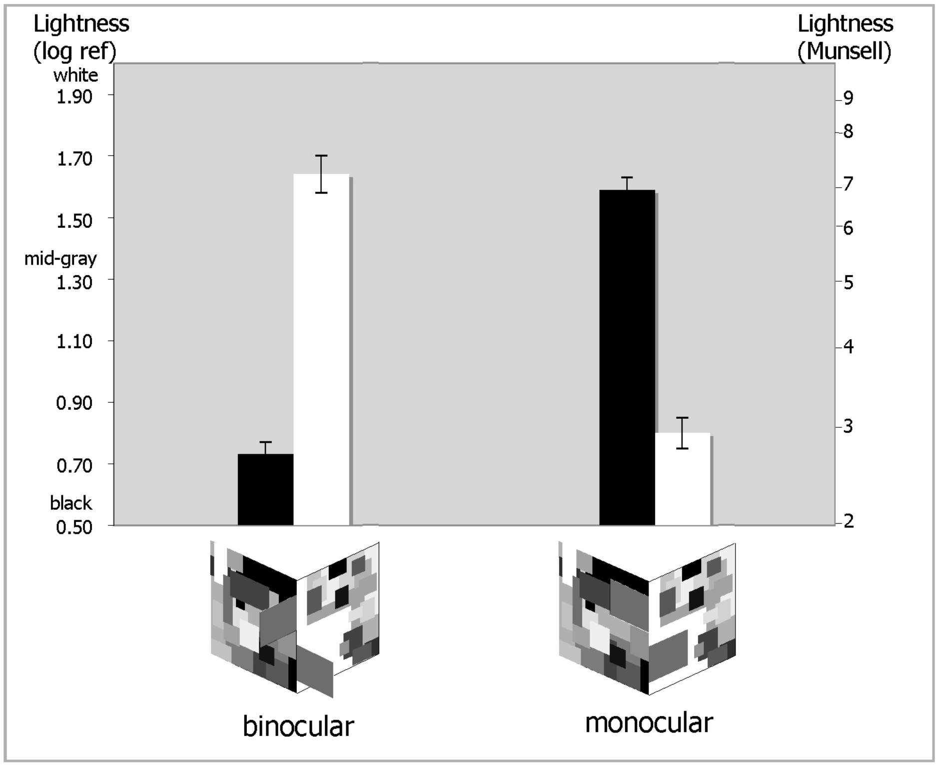

Figure 7: Experiment 2. Target lightness in the monocular and binocular conditions when both sides of the display are articulated. Lightness of the upper, lighted black target shown in black. Lightness of the lower, shadowed white target shown in white.

A repeated measures ANOVA with condition (binocular vs. monocular) as a between-subjects factor and target (upper vs. lower) as a within-subjects factor did not reveal a significant main effect of target or condition. However, it revealed a Target x Condition interaction, $F(1,38) = 263.14$, $p < 0.001$ (see Figure 7).

Planned comparisons further explored the interaction between target and condition. As in Experiment 1, paired *t*-tests revealed that the two equiluminant targets differed in lightness within both the binocular, $t(19) = -11.70$, $p < 0.001$, and the monocular conditions, $t(19) = 11.26$, $p = 0.001$. As in Experiment 1, the target that appeared coplanar with the lighted side of the display was perceived as significantly darker than the target that appeared coplanar with the shadowed background, in both conditions. This within-condition depth effect, measured as the difference in lightness between the two equiluminant targets that are, within a condition, perceived as coplanar with different sides of the display did not significantly differ between conditions: it yielded 0.91 log reflectance (equivalent to 4.5 Munsell units) in the binocular and 0.78 log reflectance (equivalent to 3.75 Munsell units) in the monocular condition.

Again, as in Experiment 1, an independent *t*-test revealed that the perceived lightness of each target varied as a function of the plane to which the target is perceived to belong. The lower, white target appeared light gray (1.64 log reflectance, equivalent to Munsell 7.25) when perceived coplanar with the shadowed side of the display in the binocular condition, but dark gray (nearly black, 0.80 log reflectance, equivalent to Munsell 3.0), when perceived coplanar with the lighted side of the display in the monocular condition, $t(38) = 10.66$, $p < 0.001$. The upper, black target, appeared nearly black (0.73 log reflectance, equivalent to Munsell 2.75), when perceived coplanar with the lighted side of the display, in the binocular condition, but light gray (1.59 log reflectance, equivalent to Munsell 6.8) when perceived coplanar with the shadowed side of the display, in the monocular condition, $t(38) = -15.62$, $p < 0.001$. The between-condition depth effect, measured as the difference in lightness of each target when it appeared coplanar with one adjacent luminance (side of the display) in the binocular condition and the other adjacent luminance (side of the display) in the monocular condition did not significantly differ for the two targets: it yielded 0.86 log reflectance (equivalent to 4.0 Munsell units) for the upper, black target and 0.84 log reflectance (equivalent to 4.2 Munsell units) for the lower, white target.

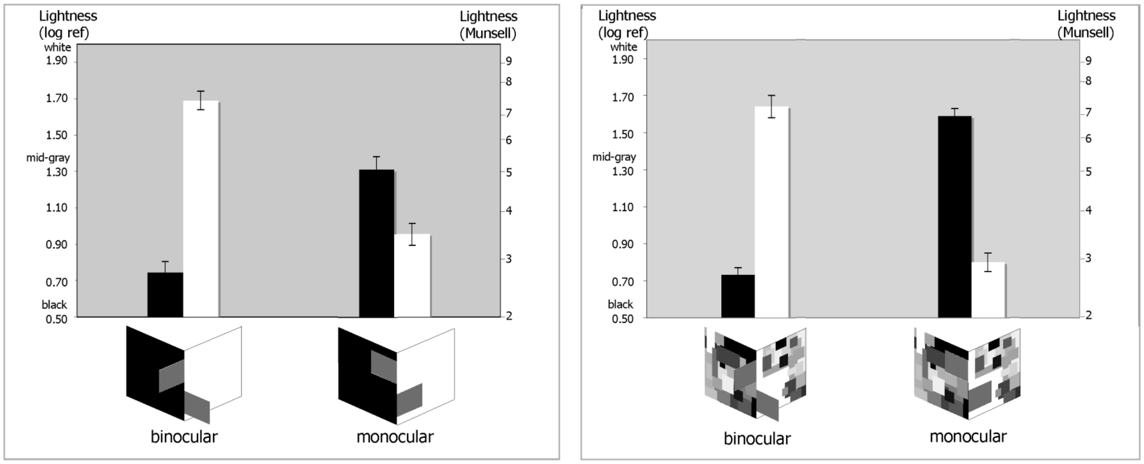

Figure 8: Comparison of the results in Experiment 1 and Experiment 2. Mean target lightness in the monocular and binocular conditions when the sides of the display are not articulated (Experiment 1, left) and when they are articulated (Experiment 2, right). The upper black target is shown in black and the lower white target shown in white.

In order to directly assess the effects of articulation on the depth effect, Experiment 1 (no articulation) and Experiment 2 (articulation) were compared using a repeated-measures ANOVA with condition (binocular vs. monocular) and experiment (1vs, 2) as a between-subjects factors and target (upper vs. lower) as a within-subjects factor. The ANOVA revealed a significant main effect of target, F (1,76) = 15.95, $p <$ 0.001; overall, the lower, white target was perceived as lighter (M = 1.27, SE = 0.03) than the equiluminant lighted black target (M=1.09, SE = 0.03). However, as suggested by the results of each of the two experiments alone and a Target x Experiment interaction, $F(1,76) = 6.62$, $p < 0.05$, the source of this main effect is only in Experiment 1 (main effect of target in Experiment 2 not significant). As expected, the ANOVA revealed a Target x Condition interaction, $F(1,76) = 283.00$, $p < 0.0001$. In both experiments, target lightness changed as a function of coplanar adjacent luminance: the lightness of the two targets perceived as coplanar with two different adjacent luminance is different and changes significantly when the perceived coplanar adjacent luminance changes.

Finally, an ANOVA revealed a Target x Condition x Experiment interaction, $F(1,76) = 5.08$, $p < 0.05$. To further explore this interaction, planned comparisons compared the lightness of each target in the binocular and in the monocular condition across the two experiments.

Independent *t*-tests showed that there was no difference in lightness matches in the binocular condition for either the upper or lower target when compared across experiments (both *t*s < 1, *ns*). Likewise, the within-condition depth effect in the binocular condition did not differ significantly in magnitude across the two experiments, $t < 1$, *ns* (4.8 Munsell units in Experiment 1 vs. 4.5 Munsell units in Experiment 2). In the monocular condition, the difference in lightness for the lower target that was perceived as coplanar with the lighted side of the display did not reach significance ($t(38) = 1.70$, $p = 0.07$) across experiments. However, the upper target, perceived as coplanar with the shadowed black side of the display, appeared significantly lighter in Experiment 2 than in Experiment 1, $t(38) = 4.21$, $p < 0.001$. In accordance with this, the size of the between-condition depth effect was significantly larger in Experiment 2 for the upper ($t(38) = 2.85$, $p < 0.01$), but not for the lower target ($t < 1$, *ns*). Also, the within-condition depth effect was significantly larger in the monocular condition of Experiment 2 than in the monocular condition of Experiment 1 (3.8 compared to 1.6 Munsell units; $t(38) = 4.22$, $p < 0.001$).

Discussion

The basic effect of perceived position on lightness established in Experiment 1 was replicated in Experiment 2, both when the two targets were compared within each condition (monocular vs. binocular) and when the same target was compared across conditions.

The anchoring theory predictions regarding the effect of articulation on lightness of the target coplanar with the shadowed side of the display and consequently, the depth effect were supported, but only in the monocular and not in the binocular condition.

In the binocular condition, the comparison across experiments showed no significant difference in lightness for any of the two targets. It is possible that articulation did not have an effect on lightness because the perceived difference between the two targets in the binocular condition of Experiment 1 was already quite large (4.8 Munsell units), and there was not much room for the target coplanar with the shadowed side of the display to move upward. Keep in mind that the anchoring theory always predicts that this target will appear slightly darker than white due to co-determination (Kardos, 1934). In other words, even though the lightness of this target is mostly determined within its local (coplanar) framework, there is always some influence of the global framework.

If articulation didn't have an effect in the binocular condition because there was no room for the target coplanar with the shadowed side to move upwards, in the monocular condition there was plenty of room for that target to move, given that in Experiment 1 it was perceived as middle gray. Indeed, in the monocular condition of Experiment 2, the target coplanar with the shadowed side of the display appeared significantly lighter than in Experiment 1 (Munsell 6.8, compared to Munsell 5.2) and the within-condition depth effect was significantly larger (3.8 Munsell units, compared to 1.6 Munsell units).

As predicted by the anchoring theory, the target perceived as coplanar with the lighted side of the display did not appear different in lightness across experiments. This is expected, because the lightness of this target is determined in relation to the same highest luminance in both local and global framework, so any change in framework strength would not cause a change in the lightness computation.

The effect of articulation on the depth effect is also manifested in the fact that when the sides of the display were articulated, in Experiment 2, the between-condition depth effect was equal for each of the two targets, unlike in Experiment 1. Also, unlike in Experiment 1, the two targets that were perceived as coplanar with the same adjacent luminance across conditions appeared equal in lightness.

The results that articulation of the planes significantly increases the depth effect is consistent with the findings of Schirillo and Arend (1995), who obtained larger depth effects (6 Munsell units) when using a richly articulated version of the parallel planes display than Schirillo, Reeves & Arend (1990) who used a poorly articulated version of the same display (2 - 2.5 Munsell units). It is also consistent with the Gilchrist et al. (1999) interpretation of the findings of Wishart et al. (1997) showing that the illusory difference in lightness between two patches that are perceived to belong to different planes in the Adelson corrugated mondrian illusion practically disappears when the planes are not articulated, but consist of only one or two surfaces of different shades of gray.

When considering the role of articulation on lightness in the light of the results of Experiment 2, one hypothesis, consistent with the differential effect of articulation on lightness in the monocular and the binocular condition, comes to mind. It is possible that articulation does not influence framework strength directly, but indirectly, by strengthening the segregation of frameworks. In other words, articulation might be the factor that facilitates grouping of elements within a visual field into frameworks, when other grouping factors are not strong enough. If this interpretation were correct, articulation would affect lightness only when frameworks within a visual field were not well segregated, like in the monocular condition, but not when segregation in depth were supported by multiple depth cues, like in the binocular condition (as discussed in Experiment 1). Due to the initially strong segregation, increasing or decreasing articulation in the binocular condition would have no further effect on framework strength and thus the weight it has in lightness computation. However, further research is necessary to test this assumption.

Experiment 2A: The source of the articulation effect

To test the prediction of the anchoring theory that articulation of the shadowed side of the display will have a bigger effect on the lightness of the coplanar target, and thus the size of the depth effect, than the articulation of the lighted side, in Experiment 2A only one side of the display was articulated at a time: either the shadowed side (articulation shadow condition) or the lighted side (articulation lighted condition). The results were compared with those obtained in Experiment 1, in which neither side of the display was articulated (no articulation condition) and Experiment 2, in which both sides of the display were articulated (articulation-both condition).

The anchoring theory predicts that the lightness of the target perceived as coplanar with the lighted side should not change significantly across all four conditions, given that both locally and globally it is perceived in relation the same highest luminance. In contrast, the target perceived as coplanar with the shadowed side of the display should appear significantly lighter when this side of the display is articulated (the articulation shadow and the articulation both conditions), than when it is not articulated (no articulation or articulation spotlight condition). Also, in the articulation spotlight condition, the target perceived as coplanar with the shadowed side of the display should not change in lightness when compared to the no articulation condition (Experiment 1), because in both conditions the local framework to which the target belongs is not articulated.

Given that in Experiment 2 the articulation affected target lightness only in the monocular but not in the binocular condition, in Experiment 2A the display was presented only monocularly in all conditions.

Method

Experiment 2A was identical to Experiment 2 in all respects except that only one side of the dihedral display was articulated in each condition. In the articulation spotlight condition only the lighted side of the display was covered with the mondrian pattern, identical to the pattern in Experiment 2, while the shadowed side of the display was covered with black Color-aid paper, reflectance 3%, as in Experiment 1. In the articulation shadow condition only the shadowed side of the display was covered with the mondrian pattern, identical to that in Experiment 2, while the lighted side of the display was covered with white paper, reflectance 90%, as in Experiment 1.

A separate group of 20 participants viewed the display in each condition. Based on the exclusion criteria 2 observers were excluded (and replaced), as they were identified as outliers: one from the articulation spotlight and one from the articulation shadow condition.

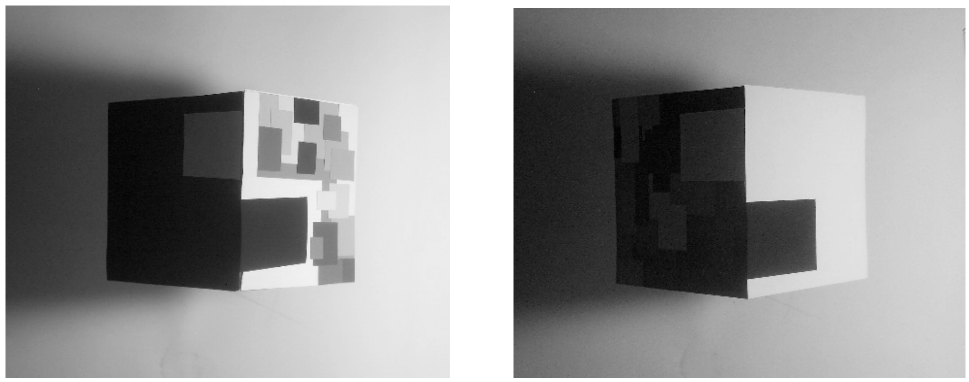

Figure 9: A photograph of the display in articulation spotlight (on the left) and articulation shadow conditions (on the right), from the observer's viewpoint.

Results

Mean lightness matches for each target in all four conditions are plotted in Figure 10.

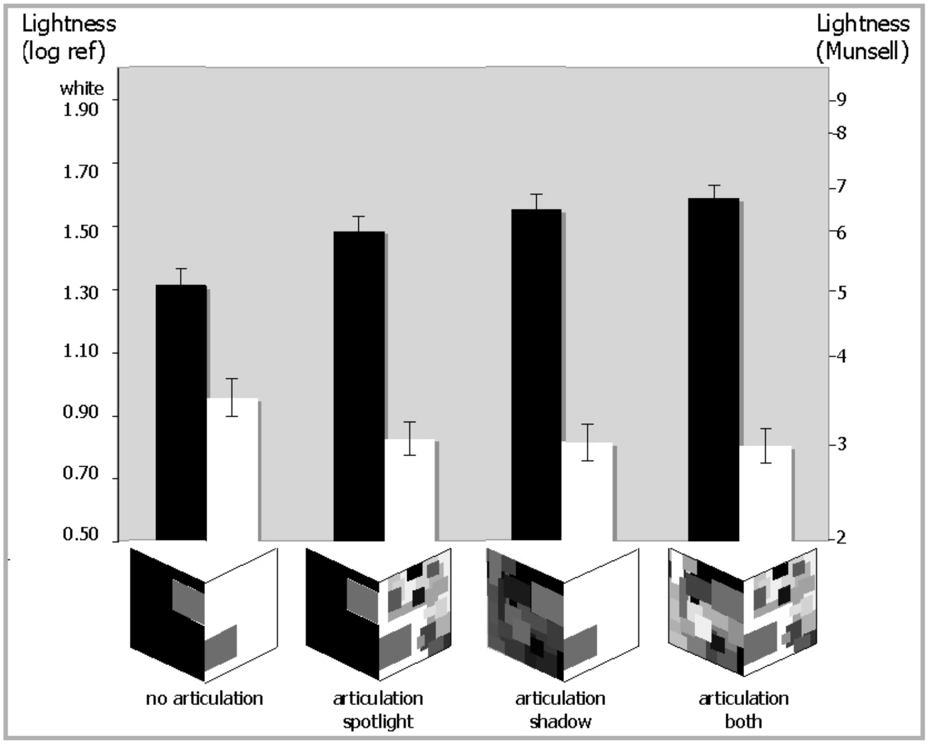

Figure 10: Target lightness in Experiment 2A and the monocular conditions of Experiments 1 and 2.

A repeated measures 4 x 2 ANOVA with condition (4 articulation conditions) as a between-subjects factor and target (upper vs. lower) as a within-subjects factor revealed a significant main effect of target, $F(3,76) = 256.71$, $p < 0.0001$. Overall, the lower, white target, perceived as coplanar with the lighted side of the display appeared darker (M = 0.85, SE = 0.03) than the upper, black target, perceived as coplanar with the shadowed side of the display (M = 1.49, SE = 0.02). The ANOVA also revealed a Target x Condition interaction, $F(3,76) = 5.91$, $p < 0.001$ (see Figure 10).

To further investigate this interaction, separate one-way ANOVAs compared the mean lightness values for each target. The lightness of the lower white target, perceived as coplanar with the lighted side of the display, did not vary significantly, $F(3,76) = 1.57$,

$p = 0.2$. Tukey HSD tests show that this target did not significantly differ in lightness across any two articulation conditions.

However, for the upper, black target, perceived as coplanar with the shadowed side of the display, the ANOVA revealed a significant main effect of condition, $F(3,76) = 7.15$, $p < 0.001$. Tukey HSD tests show that this target is perceived as significantly darker in the no articulation condition than any other condition (articulation spotlight, $p < 0.05$; articulation shadow, $p < 0.01$; articulation both, $p < 0.001$). There were no significant differences in target lightness between the articulation shadow, articulation spotlight and articulation both conditions.

Finally, the size of the within-condition depth effect was also compared across four articulation conditions in a separate one-way ANOVA, which also revealed a significant main effect of condition, $F(3,76) = 6.10$, $p < 0.01$. The results of Tukey HSD test correspond to the results for the upper target. In the no articulation condition the depth effect was significantly smaller (0.35 log reflectance, equivalent to Munsell 1.6) than in any other articulation condition (articulation spotlight, 0.67 log reflectance, equivalent to Munsell 3.05, $p < 0.05$; articulation shadow: 0.74 log reflectance, equivalent to Munsell 3.5, $p < 0.01$; articulation both, 0.79 log reflectance, equivalent to Munsell 3.75, $p < 0.001$). Also, the within-condition depth effect did not differ in size between the articulation shadow, articulation spotlight and articulation both conditions.

Discussion

As predicted by the anchoring theory, the target perceived coplanar with the lighted side of the display was not affected by any of the articulation conditions, regardless of side or sides articulated.

However, contrary to the predictions of the anchoring theory, the target that appeared coplanar with the shadowed side of the display appeared lighter when any of the sides of the display was articulated, not only the shadowed side. Although mean lightness matches across conditions show a trend in the direction of the anchoring theory predictions (higher in the articulation shadow and articulation both conditions than in the articulation spotlight condition), statistical tests did not reveal any significant difference across the three articulation conditions. The articulation of the non-coplanar, lighted side of the display seems has a similar same effect on lightness of the shadowed target as the articulation of the coplanar, shadowed side of the display.

Consequently, the size of the within-condition depth effect increased with articulation, but again, contrary to the predictions of the anchoring theory, the effect was larger in all three articulation conditions, and not only those in which the shadowed side of the display was articulated.

One possibility is that articulation affects lightness by increasing the segregation between the sides of the display (i.e. local frameworks) based on the difference in structure of the two sides (opposite of grouping by similarity) when only one side of the display is articulated and the other is not. If this is the case, the articulation of any one side of the display would strengthen the segregation of the two depth frameworks and increase the weight of each target's local framework. Consequently, this should increase the lightness of the target coplanar with the shadowed side of the display in the articulation spotlight and the articulation shadow condition, while the effect on lightness of the target coplanar with the lighted side of the display would be, again, far smaller, as was obtained.

The empirical findings that articulation of the planes of the display can affect target lightness represents an interesting challenge for many theories of lightness that do not assign a theoretical role to articulation. It is problematic for the high-level neo-Helmholzian inferential theories according to which the visual system is estimating and discounting intensity and chromaticity of illumination in the scene (Boyaci et al, 2003, 2006; Ripamonti et al. 2004). It is not clear how increasing or decreasing the articulation can change the parameters that guide the visual system's estimate of the illumination model in a given scene. The findings are also problematic for low-level filtering models according to which target lightness is computed based on the local retinal ratios (Blakeslee and McCourt, 1999, 2003). In Experiment 2, the change in lightness of the target coplanar with the shadowed side of the display due to articulation goes in the opposite direction of that predicted based on the change in average luminance of the target's coplanar background. Articulating the shadowed side of the display by adding patches of higher reflectance than black next to the coplanar target should, according to the local contrast account, cause darkening and not lightening of this target.

From the perspective of the anchoring theory, it would be good to replicate the findings that we have obtained and to explore why target lightness can be affected by articulation of the plane to which the target does not belong, and to test the specific hypothesis that articulation changes the strength of segregation through grouping based on similarity. One possible way to explore this is to systematically vary articulation, while controlling for similarity in local frameworks of complex displays and to vary similarity while controlling for articulation.

Experiment 3: The role of adjacency in the effect of depth on lightness: does target lightness depend on the adjacent luminance or the highest luminance in the plane?

According to coplanar ratio principle in its original formulation (Gilchrist, 1977, 1980) target lightness is a function of the adjacent coplanar luminance. Therefore, the coplanar ratio principle predicts that target lightness will change significantly if the adjacent coplanar luminance changes. To the extent to which it emphasizes local luminance ratios, this view is similar to the low-level theories of lightness that predict a change in target lightness as a function of local contrast (Cornsweet, 1970; Jameson & Hurvich, 1964; Reid & Shapley, 1988; Blakeslee & McCourt, 1999).

However, according to the anchoring theory adjacency does not play a critical role in lightness computation. Instead, lightness is a function of the highest luminance in the framework(s) to which the target belongs. When the local framework is equivalent to a plane, as in Experiments 1 and 2, target lightness will depend on the highest luminance in the plane, regardless of its position relative to the target.

The hypothesis that the lightness of any surface can be computed based on the highest luminance within a group of surfaces (i.e. framework) is based on the assumption that the visual system can compute luminance ratios not only between adjacent surfaces, as Wallach showed (1948), but between any two surfaces within an image. Land and McCann (1971) were the first to propose this idea and empirically demonstrate that the visual system is able to correctly extract ratios between any two remote surfaces in the visual field. They proposed an algorithm according to which this is achieved by mathematically integrating local ratios at the edges of adjacent surfaces along a provisional path between the two compared surfaces (Land & McCann, 1971). According to Land & McCann's edge integration model, because the estimation of ratios occurs between closely-spaced receptors, illumination variations, which are most of the time gradual, do not affect the computation across such a narrow area and can be disregarded. Other models of edge integration however assume that the visual system is conducting *a classified edge integration*, first classifying the edges in the image as either illumination edges, reflectance edges or depth boundaries and then integrating ratios within each class separately (Bergström, 1977; Gilchrist, 1979).

Although the exact mechanism is unknown, there is substantial empirical evidence that some integration (i.e., computation) does occur among successive edges in the image (Koffka, 1935; Arend, Buehler and Lockhead, 1971; Arend, 1973; Gilchrist et al., 1983; Whittle and Challands, 1969). Such a mechanism would allow any surface in a framework to be compared with the highest luminance within that framework, for the purpose of lightness computation, as proposed by the anchoring theory.

The goal of Experiment 3 was to test opposing predictions of the coplanar ratio principle and the anchoring theory about the role of the adjacent coplanar luminance in the effect of depth on lightness. To test if target lightness depends on the adjacent luminance or the highest luminance in the plane, irrespective of its location relative to the target, the position of the highest luminance patch on the lighted side of the display relative to the lower target was varied across conditions. Note that when the display is viewed monocularly, varying the position of the highest luminance on the lighted side of the display is equivalent to varying the coplanar adjacent luminance of the lower target because in the monocular condition this target appears coplanar to the lighted side.

In one condition, the highest luminance patch was retinally adjacent to the lower target (adjacent condition, equivalent to the monocular condition of Experiment 2). In the other condition, the highest luminance patch was remote from the lower target, at the opposite edge of the mondrian pattern, while patches lower in luminance were retinally adjacent to the target (remote condition).

If target lightness depends on the adjacent luminance and not the highest luminance in the plane, as predicted by the coplanar ratio principle, then the lightness of the lower target will differ across conditions. The target will be perceived as lighter in the remote condition, when the adjacent coplanar luminance is lower, than in the adjacent condition. Consequently, the within-condition depth effect will be smaller in the remote than in the adjacent condition (monocular condition of Experiment 2)

If target lightness depends on the highest luminance within a plane, irrespective of its location in the plane, as predicted by the anchoring theory, then the lightness of the lower target and the within-condition depth effect will be the same in the two conditions.

As the coplanar adjacent luminance of the upper target remains the same across conditions, both accounts predict no change in lightness of this target.

Method

Experiment 3 was identical to Experiment 2 in all respects except (1) the display was viewed only monocularly and (2) the mondrian pattern on the lighted side of the display was changed so that the white patch was no longer retinally adjacent to the lower target, which in the monocular condition appeared coplanar with the lighted side.

The new mondrian pattern consisted of 20 patches of different reflectance from white to black. The structure of the pattern was pseudorandom, but the distribution of reflectances was not. Instead, the white patch (the highest luminance in the pattern) was placed remote from the target, at the opposite end of the pattern (the upper right corner; compare the position of the white patch on the right side of the displays in Figure 11), while the patches adjacent to the target varied from dark to middle gray (from 9% to 22% reflectance). The distribution of the rest of the patches in the display was biased, so that the patches of lower reflectance were nearer and the patches of higher reflectance were farther from the target. The mondrian pattern on the shadowed side of the display was identical to that in Experiment 2.

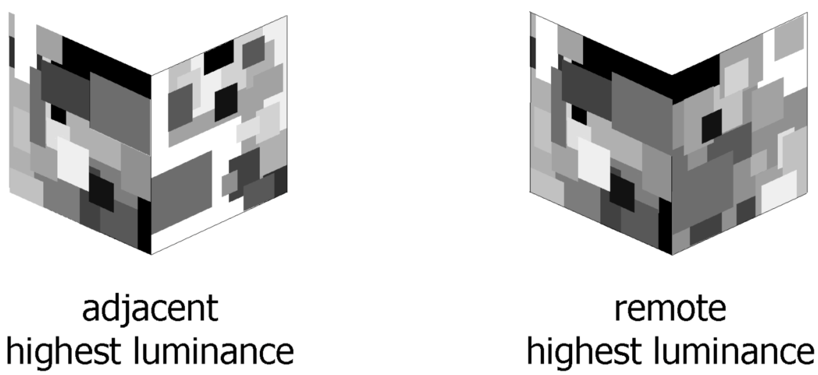

Figure 11: A perspective view that illustrates the perceived spatial arrangement (not the observer's retinal image) and the reflectance pattern in which the highest luminance was adjacent to the target (Experiment 2, left) and when it was in a remote location (Experiment 3, right).

The luminance of the targets was 17.6 cd/m^2, the luminance of the white patch on the lighted side of the display was 530 cd/m^2 and the luminance of the white patch in the shadowed side of the display was 14.4 cd/m^2.

A separate group of 20 observers viewed the display monocularly, through a pinhole and judged the target lightness of both targets using a Munsell chart. These lightness matches (remote condition) were compared to those from the monocular condition of Experiment 2 where the highest luminance was immediately adjacent to the apparently coplanar target (adjacent condition).

Results

The mean lightness matches for each target in the remote and the adjacent conditions are plotted in Figure 12.

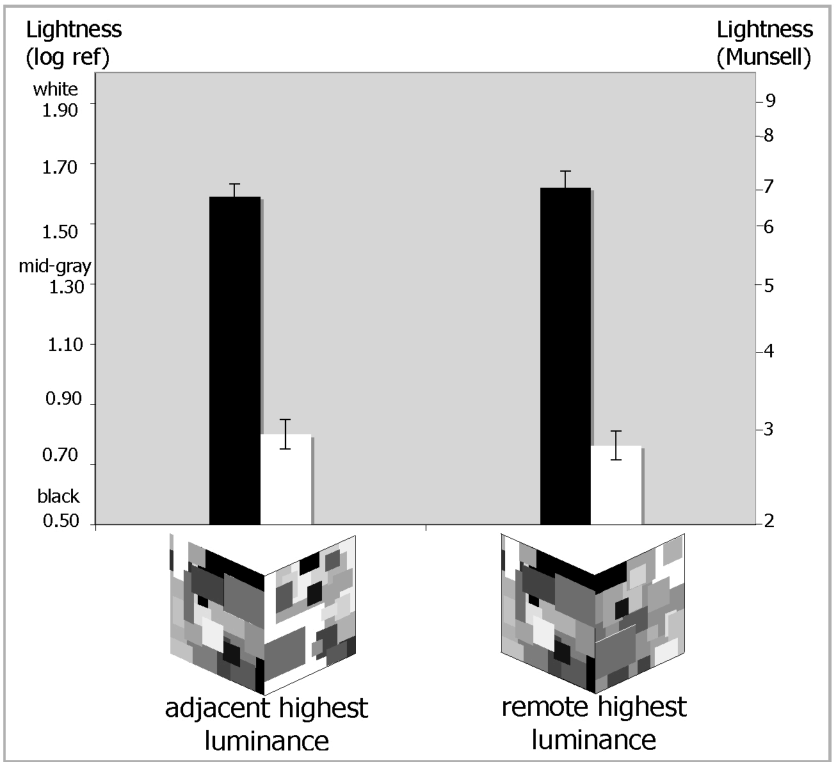

Figure 12: Experiment 3. Target lightness when the highest luminance is adjacent and when it is remote relative to the lower target. Lightness of the upper, lighted black target shown in black. Lightness of the lower, shadowed white target shown in white.

A repeated measures ANOVA with condition (adjacent - remote) as a between-subjects factor and target (upper - lower) as a within-subjects factor revealed a significant main effect of target, $F(1, 38) = 295.35$, $p < 0.001$. Overall, the upper target, perceived coplanar with the shadowed side of the display appeared lighter (M = 1.60, SE = 0.03) than the lower target (M = 0.78, SE = 0.04), perceived as coplanar with the shadowed side of the display. The main effect of condition as well as Target x Condition interaction were not significant, $F < 1$, *ns* (see Figure 12).

The size of the within-condition depth effect in the adjacent condition (0.79 log reflectance, equivalent to Munsell 3.75) did not differ significantly from that in the remote condition (0.86 log reflectance, equivalent to Munsell 4.15), $t < 1$, *ns*.

Discussion

The within-condition depth effect obtained when the highest luminance was adjacent to the target was replicated when the highest luminance was remote: the lower target, which appeared coplanar to the lighted side of the display appeared darker than the upper target, which appeared coplanar to the shadowed side.

The results, however, clearly support the predictions of the anchoring theory: whether the highest luminance was adjacent or remote relative to the lower target, neither target lightness nor the within-condition depth effect changed, suggesting that the position of the highest luminance in the plane relative to the target is not relevant for lightness computation.

Note that the anchoring theory actually proposes "an edge-integrated version of the coplanar ratio principle". Compared to the original version (Gilchrist, 1977, 1980), this integrated anchoring version (1) explicitly states the dependence of target lightness on the highest luminance in a depth framework and (2) assumes that the process of comparison of any surface with the highest luminance is possible based on the integration of successive edges within a plane. In other words, the integrated coplanar ratio principle is equivalent to the proposal that the anchor determines lightness anywhere within a local framework that is segregated by a depth boundary.

The results are consistent with the results of Cataliotti & Gilchrist (1995) who in a series of simple experiments explored the factors causing the darkening of a Gelb square. As described in the introduction, when an isolated piece of black paper is presented in the spotlight it will appear white (an illusion known as Gelb effect, described by Koffka, 1935), but it will significantly darken when a piece of paper of higher reflectance is introduced into the spotlight, adjacent to it. Cataliotti & Gilchrist argue that this darkening of the Gelb square is a function of anchoring (i.e. highest luminance in the framework) and not a function of distance as predicted by a local contrast account. They show that when a row of squares higher in reflectance (luminance) is introduced into the spotlight, adjacent to the black square, the degree of its darkening depends on the luminance ratio between the black square and the highest luminance in the group and not on the retinal or perceived distance between them: the amount of darkening was the same whether the highest luminance patch was adjacent to the black square or remote from it at the opposite end of the row of squares (Cataliotti & Gilchrist, 1995). Cataliotti & Gilchrist found the same effect in an experiment using a Mondrian world set-up, a trapezoidal shaped room filling the observer's entire visual field, whose walls were completely covered with a mondrian pattern consisting solely of dark gray and black patches. Introducing a white patch into the Mondrian world caused the darkening of all other patches in the display and not only those adjacent to it. The amount of darkening was, contrary to the local contrast prediction, equal across patches and not a function of distance from the white patch (Cataliotti & Gilchrist, 1995).

These results, together with the results of Experiment 3 represent a challenge for the low-level theories (Cornsweet, 1970; Jameson & Hurvich, 1964; Reid & Shapley, 1988; Blakeslee & McCourt, 1999) emphasizing the importance of local contrast, which predict that a change in local lightness ratios (either retinal or coplanar) will always cause a change in lightness.

Experiment 4: Does target lightness depend on the highest luminance within a plane or the highest luminance within a field of illumination?

In the previous experiments, as well as the original experiments by Gilchrist (1977, 1980) the analysis of the stimulus in terms of frameworks is relatively simple. When depth boundaries are the main segregation factor within an image, the local frameworks are equivalent to depth planes; in such cases, according to the anchoring theory, local target lightness will be determined relative to the highest luminance in the plane. Although in the previous experiments the sides of the display were differently illuminated, there was no visible penumbra that would segregate the display into different frameworks of illumination. However, it is often the case that a plane is not uniformly illuminated. In the paper introducing the anchoring theory, Gilchrist et al. (1999) ask: "What happens, for example, when a shadow falls across half of a set of coplanar regions?". In other words, how is lightness computed when a plane contains multiple fields of illumination? Experiment 4 aims to provide an answer to this question.

This question is relevant from the perspective of the anchoring theory, because it explores the interaction between the two main factors by which the visual system segregates a complex image into frameworks for the purpose of lightness computation: (1) depth boundaries which segregate the image into different depth frameworks (planes) and (2) penumbrae which segregate the image into different frameworks of illumination. The question arises: when both of these segregation factors are available in the image, which determines the framework within which the target is assigned a lightness value. In other words: does target lightness depend on the highest luminance within a depth framework (plane) or the highest luminance within a framework of illumination?

In Experiment 4 the display was changed so that the lighted side of the display was not uniformly illuminated. Instead, only half of it was in bright illumination (spotlight) while the other half was in dim illumination (shadow). In terms of the anchoring theory, the display was segregated by a depth boundary into two local depth frameworks (planes, i.e. sides of the display), but, in addition, one of these depth frameworks (the lighted side) was segregated by a penumbra into two frameworks of illumination (the shadow and the spotlight), each having a different highest luminance.

To establish if target lightness depends on the highest luminance in the plane or the highest luminance in the field of illumination two factors were varied systematically: (1) the perceived plane of the target and (2) the perceived field of illumination of the target.

(1)The perceived plane of the target was varied by varying the viewing conditions, just as in Experiments 1 and 2. The display contained only the lower target, extending from the shadowed side of the display. When viewed binocularly, the display was perceived veridically in depth: the target appeared coplanar to the shadowed side of the display. However, when viewed monocularly, because it was trimmed to match the linear perspective projection of a rectangle lying on the lighted side of the display (which formed its primary retinal background) the target appeared coplanar to that side.

(2) The perceived field of illumination of the target in the monocular condition[30] was varied by varying the position of the spotlight on the lighted side of the display relative to the target.

[30] Note that the target's perceived field of illumination could be varied only in the monocular condition. In the binocular condition, the target always appeared as extending from the shadowed side of the display. Thus, it belonged to that field of illumination.

In one condition, the spotlight covered the right half of the lighted side of the display, so that when viewed monocularly, the target appeared to lie in the shadowed half of the lighted side of the display (the shadow condition). In this condition, the highest luminance in the target's field of illumination under monocular viewing was the same as that under binocular viewing, when the target appeared coplanar to the shadowed side of the display.[31] Thus, in the shadow condition, when the perceived plane of the target changed with the change in viewing conditions, the highest luminance in the target's framework of illumination remained the same across viewing conditions.

In the other condition (the spotlight condition), the spotlight covered the left half of the lighted side of the display, so that when viewed monocularly, the target appeared to lie in the lighted half of the lighted side of the display In this condition, the highest luminance in the target's field of illumination in the monocular condition was thirty times higher than that in the binocular condition, in which the target appeared coplanar to the shadowed side of the display. Thus, in the spotlight condition, when the perceived plane of the target changed with the change in viewing conditions, the highest luminance in the framework of illumination of the target also changed across conditions (See Figure 13).

Note that in both the shadow and the spotlight condition, the change in perceived plane was accompanied by a change in the highest coplanar luminance. When the target appeared coplanar to the lighted side of the display in the monocular condition, the highest coplanar luminance was thirty times higher than when the target appears coplanar to the shadowed side of the display, in the binocular condition, just as in Experiments 1-3. Therefore, if lightness depends on the highest luminance in the plane the target should

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[31] In the binocular condition, the highest luminance in the shadowed framework of illumination was equivalent to the target luminance.

appear significantly darker in the monocular condition, in which the highest coplanar luminance is thirty times higher than in the binocular condition, irrespective of its field of illumination. In other words, if target lightness depends on the highest luminance in the plane, the between-conditions depth effect will be the same in both the spotlight and the shadow condition.

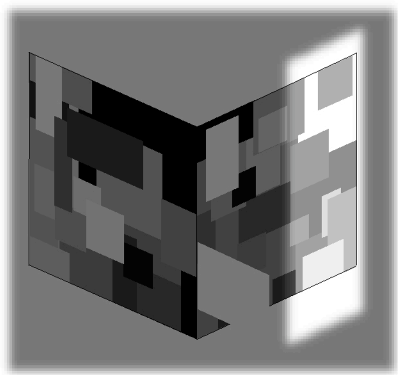
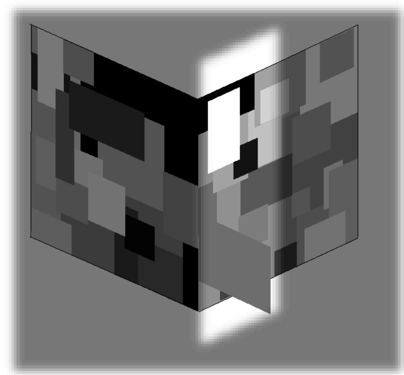
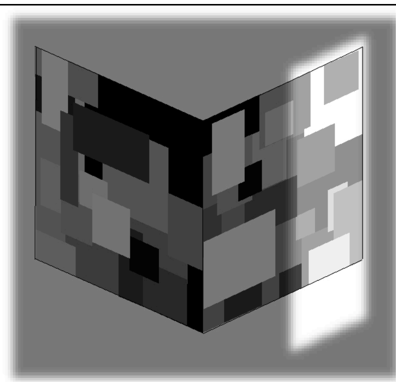
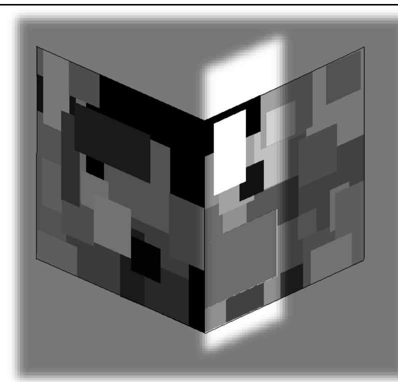
	Shadow	Spotlight
Binocular		
Monocular		
Change across viewing conditions	Different coplanar luminance & Same highest luminance in the framework of illumination	Different coplanar luminance & Different highest luminance in the framework of illumination

Figure 13: A perspective view that illustrates the perceived spatial arrangement (not the observers' retinal image) and the perceived field of illumination across four conditions. Changes in the highest luminance across viewing conditions are summarized at the bottom.

However, if the target lightness depends on the highest luminance in the framework of illumination, then target lightness will change across viewing conditions only in the spotlight condition and not in the shadow condition.

Method

Experiment 4 was identical to Experiment 3 in all respects except (1) the display contained only the lower target (white target extending from the dimly illuminated side of the display) and (2) the illumination of the right, lighted side of the display was not uniform. Instead, only half of the side was in bright illumination while the other half was in shadow. To achieve this, the illumination conditions in the experimental set-up were slightly changed.

Illumination conditions. The experimental scene was illuminated by two projectors, mounted on a stand positioned approximately 50 cm outside the tunnel right wall at 113 cm height (see Figure 14). The beams of both projectors passed through a square aperture in the right wall of the tunnel.

One projector (Kodak Carousell, model 800H with Raynox 100 mm -150 mm, f3.5 zoom lens) illuminated one half of the lighted side of the display. The size and shape of the illuminated field was defined by a square aperture within a metal slide inserted into the slide projector. A neutral density filter (70% transmittance) covered the aperture to reduce the amount of light and achieve the desired luminance values. Another projector (Kodak Ektagraphic model B-2, with Kodak Ektanar C 102 mm, f2.8 lens) was used to adjust the luminance value of the target. It illuminated a piece of white paper attached to the reflecting panel in the front left of the tunnel parallel to the target, which reflected the light onto the target. To eliminate a yellow tinge in the light coming from the projector, a piece of blue paper was added to the panel.

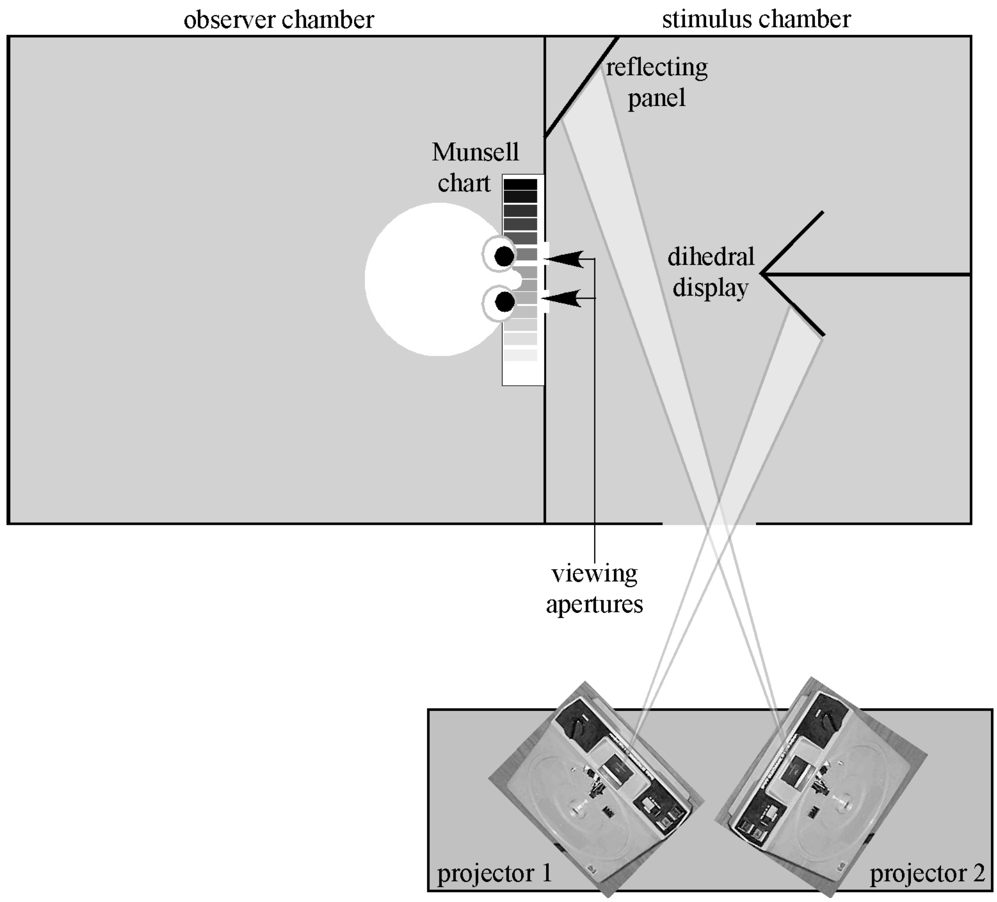


Figure 14: Plan view of the experimental apparatus in Experiment 4 (the shadow condition).

Proximal stimulus. Although the absolute level of illumination was changed, the relative luminance values were the same as in Experiment 3. The luminance of the target was 29.5 cd/m^2. The luminance of the white patch (the highest luminance) in the spotlight on the lighted side of the display was 890 cd/m^2. The luminance of the white patch (the highest luminance) in the shadowed half of the lighted side of the display was 30 cd/m^2, equal to that of the white patch in the shadowed side of the display. The luminance values in the spotlight and in the shadow condition were approximately the same (up to 4% variation, equivalent to the measuring error).

Observers. A separate group of 15 observers viewed the display in each of the four conditions (monocular and binocular, in shadow and in spotlight) and judged target lightness using the Munsell chart. Two observers in the spotlight condition (one from the monocular and one from the binocular condition) were excluded (and replaced) as they were identified as outliers.

Results

The mean target lightness matches in the four conditions are shown in Figure 15.

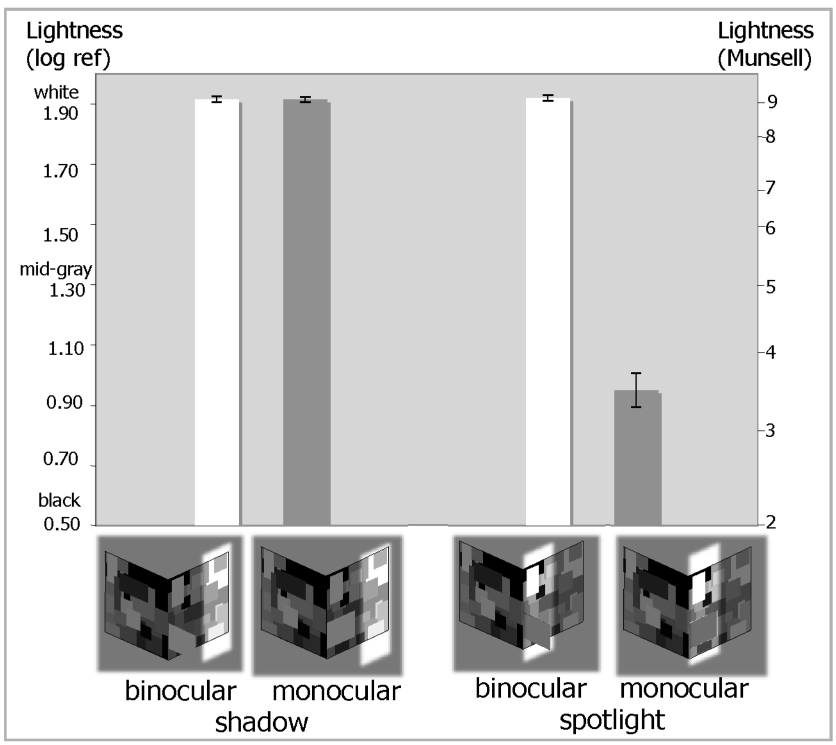


Figure 15: Experiment 4. Target lightness in the four conditions. Target lightness in binocular condition shown in white, target lightness in monocular condition shown in dark gray.

A 2 x 2 ANOVA with viewing condition (monocular vs. binocular) and field of illumination in the monocular condition (spotlight vs. shadow) as between-subjects factors revealed a significant main effect of the viewing condition, $F(1, 56) = 209.65$, $p < 0.001$ as well as significant main effect of the field of illumination, $F(1,56) = 213.46$, $p < 0.001$. Overall, the target was perceived as darker in the monocular ($M = 1.44$, $SE = 0.02$) than in the binocular condition ($M = 1.92$, $SE = 0.02$). Also, overall, the target was perceived as darker in the spotlight ($M = 1.92$, $SE = 0.02$) than in the shadow condition ($M = 1.43$, $SE = 0.02$). The ANOVA also revealed a Viewing Condition x Field of Illumination interaction, $F(1, 56) = 213.15$, $p < 0.001$ (see Figure 15).

Planned comparisons further explored the interaction between field of illumination and viewing condition. Independent *t*-tests compared the lightness of the target in its two perceived planes both in the spotlight and in the shadow. The *t*-test revealed that target lightness did not significantly change in the shadow condition ($t < 1$, *ns*); however, in the spotlight condition, the target appeared significantly lighter when it appeared coplanar to the shadowed side of the display in the binocular condition than when it appeared coplanar to the lighted side of the display in the monocular, $t(28) = 14.84$, $p < 0.001$.

Also, the size of the between-condition depth effect in the spotlight and in the shadow condition was significantly different, t(28) = 14.52, p < 0.001: while in the shadow condition, it yielded approximately 0 log reflectance (precisely: 0.0004; equivalent to 0.03 Munsell units), in the spotlight condition it was as large as 0.97 log reflectance (equivalent to 5.6 Munsell units).

Discussion

The results show that target lightness depends on the highest luminance in the framework of illumination and not the highest luminance in the plane the target is perceived to belong: target lightness changed only when a change in its perceived depth was accompanied by a change in the highest luminance in the target's field of illumination.

From the perspective of the anchoring theory, this result can be interpreted in terms of a change in grouping for lightness computation within an image. Introducing the penumbra within a plane causes its segregation into two local frameworks and the local target lightness will be determined within the new local framework. Given that local target lightness is a function of the highest luminance in the local framework, when the local highest luminance changes across conditions target lightness will also change, just like in the spotlight condition.

Note that in all the previous experiments as well as the original experiments by Gilchrist (1977, 1980) the different perceived planes of the target across conditions were also differently illuminated. Thus, the change in target lightness occurs in the context of two simultaneous changes: a change in the target's depth plane and a change in the target's field of illumination (Howe, 2006). In Experiment 4 these two factors were manipulated independently. One possible interpretation of these results is that the depth effect on lightness is mediated by a change in perceived illumination. When illumination is equivalent across planes, like in the shadow condition, target lightness remains the same despite the change in perceived depth.

These findings are consistent with those of Howe (2006) who recently conducted a series of experiments aiming to tease apart the relative contribution of coplanarity and perceived illumination in the effect of depth on lightness. He found that when the perceived illumination is held constant across conditions, the change in position across planes "affects lightness only for some subjects" and concluded that "the differences in perceived illumination seem to influence target lightness more than coplanar relations" (Howe, 2006, p. 298 - 299).

Even if such conclusion is correct, it evokes another important question and that is how the visual system obtains the information about the perceived illumination. This problem has two separate components: first, how the visual system identifies a field of illumination in the scene and second, how the illumination level is computed within the identified field.

The coplanar ratio principle does not discuss explicitly either of the two problems. It only makes an indirect reference to the importance of fields of illumination for lightness computation through the luminance range constraint.

Anchoring theory, however, by introducing the notion of frameworks, does talk about the problem of identifying units in the image within which the target lightness is determined. As discussed in the introduction, the fields of illumination segregated by the penumbra are only one kind of such units; depth planes, groups based on gestalt principles etc., are some of the others.

Although it does not explicitly propose a mechanism for estimating the illumination within a framework, the anchoring theory assumes that "perceived level of illumination is closely associated with the highest luminance in the framework" (Gilchrist et al., 1999, p. 830). This is based on empirical work by Beck (1959, 1965) and Oyama (1968) showing that perceived illumination level correlates with the highest luminance. Using the highest luminance in the framework as a proxy for the perceived illumination within that framework means that when the target moves from one local framework to another local framework that has a different highest luminance, the target lightness will change across conditions. The results of Experiment 4 are consistent with this prediction.

Note, however, that in the case where the two planes have different highest luminance, the anchoring theory would predict that the target lightness will change when the target moves across planes, even if there is no penumbra and no large luminance range in the image to signal the difference in illumination. If this prediction is correct, to conclude, based on the results of Experiment 4, that target lightness does not depend on the highest luminance in the plane (depth framework) would be misleading.

This problem will be further discussed in Experiments 6 that aims to explore the role of the luminance range in the depth effect on lightness.

Experiment 5: Is continuity within a plane necessary condition for the coplanar ratio principle to apply?

It is an explicit requirement of the coplanar ratio principle that, for surface lightness to be determined based on coplanar and not retinal ratios, that surface needs to be perceived to belong to a continuous group within a plane i.e. to have an adjacent coplanar neighbor (Gilchrist, 1977, 1980). When a single surface is isolated in space, there is no standard within its plane that can serve for comparison in the lightness computation. Gilchrist (1980) suggests that in such a case the surface lightness will be, by default determined based on retinal ratios.

But what happens when there are other surfaces present in the same plane but they are not adjacent to the target surface? Can they serve as a standard for lightness computation even if they are not immediately adjacent? In other words: is continuity within a plane necessary for the coplanar lightness computation to apply?

He and Nakayama (1992, 1994) show that the visual system prefers to make comparisons within a continuous group of surfaces rather then across open space. As this finding is replicated in many different domains (texture, motion, visual search, attention; reviewed in Nakayama et al., 1995), it is plausible to assume that it also applies to lightness. Breaking the continuity within a plane might interrupt grouping for the purposes of lightness computation and force the visual system to return to a default comparison based on retinal ratios.

To test if continuity within a plane is a necessary condition for the coplanar ratio principle to apply, the perpendicular planes setup from Experiment 1 was modified to create the conditions in which the continuity of the surfaces within a plane was disrupted:

the target was moved within its plane, away from the coplanar background, so it appeared to float in space, without any adjacent coplanar neighbor. Otherwise, the perceived depth relations remained the same. When viewed binocularly (coplanar only condition), the display was perceived veridically in depth: the dimly illuminated white target (right target)[32], appeared coplanar with the dimly illuminated black side of the display and the brightly illuminated, but equiluminant, black target (left target)[33] appeared coplanar with the brightly illuminated white side of the display. When viewed monocularly (embedded condition), the right target was perceived to lie in the middle of the lighted white side of the display, coplanar and surrounded by it and the left target was perceived to lie in the middle of the shadowed black side of the display (see Figure 16).

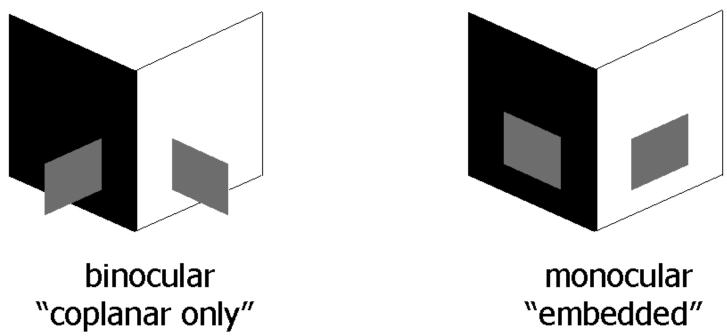


Figure 16: A perspective view that illustrates the perceived spatial arrangement (not the observer's retinal image) in the binocular and monocular conditions. Note that the actual target positions did not change and the targets appeared slightly trapezoidal in the binocular condition.

If continuity within a plane is not a necessary condition for coplanar lightness computation and mere coplanarity is sufficient, then in the coplanar only condition target

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[32] Equivalent to the lower target in Experiments 1 - 3.
[33] Equivalent to the upper target in Experiments 1 - 3.

lightness would be determined in relation to the coplanar but non-adjacent surface in the plane, just as in the binocular condition of Experiment 1. In this case, the perceived lightness of each target would significantly change with the change in the perceived plane it belongs to across conditions (between-condition depth effect). Also, the two equiluminant targets will appear significantly different within each condition, given that they are perceived as coplanar with different planes (within-condition depth effect).

If continuity within a plane is a necessary condition for coplanar lightness computation, then target lightness will not change significantly as a function of perceived position (plane). In this case, it is possible that surface lightness would be determined solely by retinal ratios. As the retinal ratios would not change across conditions, the perceived lightness for both targets would not change. Due to the local contrast effect, the right target, perceived against the lighted white side of the display would appear lighter than the left target perceived against the shadowed black side of the display.

Method

Experiment 5 was identical to Experiment 1 in all respects except that the position of the targets within the display was changed. Because of this, the shape of the targets, as well as the illumination conditions in the experimental set-up were also slightly changed. Each target was moved laterally within its own plane, so it was not adjacent to the side of the display with which it was coplanar, but separated from this side by a 2 cm gap, so that it appeared to float in front of the side of the display with which it was not coplanar.

Each target was 4.5 x 4 cm and supported by a 7 cm long rigid wire attached to side of the display the target was seen against (see Figure 17). The wire extended from the center of each side of the display in the direction of the observer's line of sight and was occluded from the observers view by the target itself.

As in Experiment 1, each target was trimmed to match the linear perspective of the rectangle forming its retinal background, so that in the monocular condition it would be seen as coplanar with that rectangle.

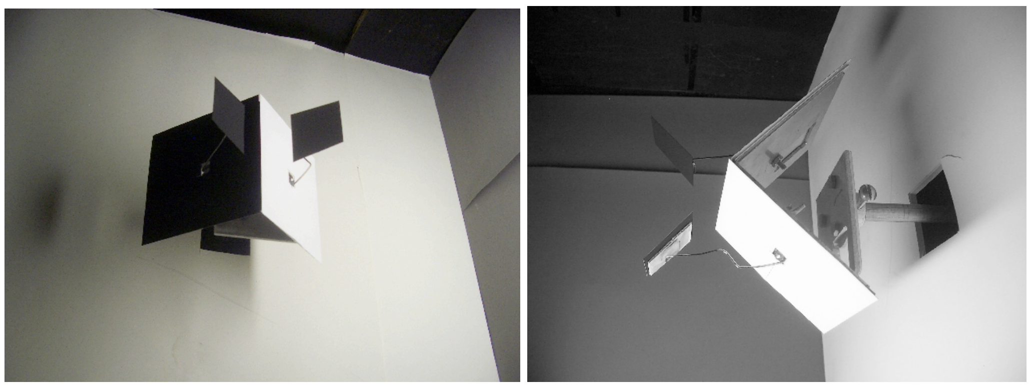

Figure 17. Stimulus set-up in Experiment 5 from two positions different from the observer position.

Illumination conditions. To avoid a visible shadow of the wire supporting the right target, floating in front of the lighted side of the display, the incandescent bulb used in Experiment 1, was replaced with a 15W fluorescent tube attached in a vertical position to the right wall of the stimulus chamber.

Proximal stimulus. Each target subtended 6.1° of visual angle horizontally and 5.5° of visual angle vertically. Although the absolute level of illumination was changed, the relative luminance values were the same as in Experiment 1. The luminance of each target was 12 cd/m^2. The luminance of the dimly illuminated black side of the display was 0.4 cd/m^2 and the luminance of the brightly illuminated white side of in the illumination of the display was 360 cd/m^2. The luminance of the background wall varied from 138 cd/m^2 just below the display to 305 cd/m^2 on the right side of the display.

Observers. A separate group of 15 observers viewed the display in the monocular and binocular conditions and judged the lightness of both targets using a Munsell chart. One observer was excluded (and replaced) from the coplanar only condition, as he was identified as an outlier.

Results

The mean lightness matches for each target in the monocular and binocular condition are plotted in Figure 18.

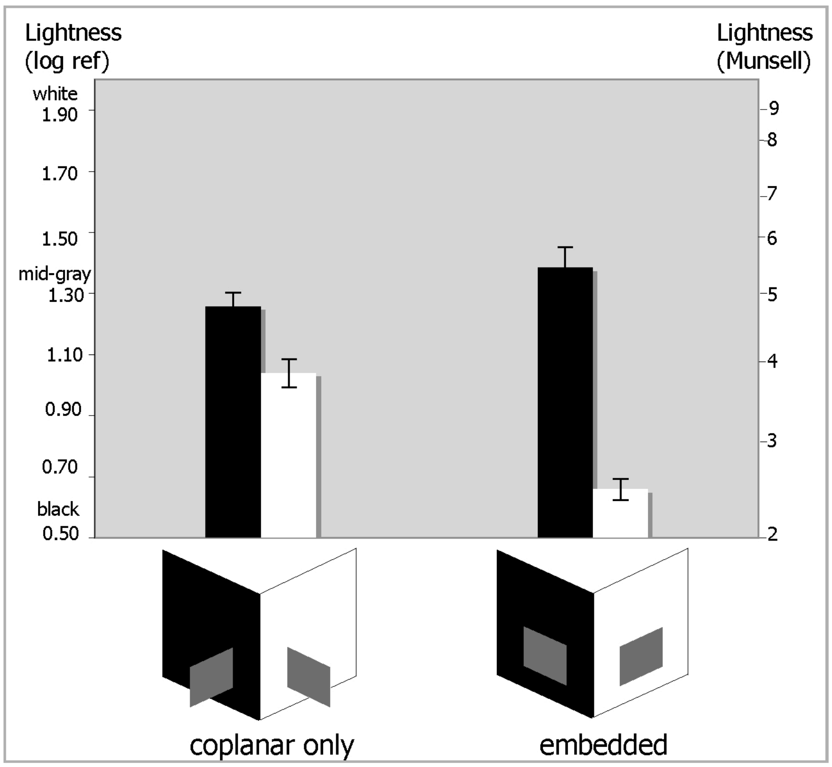

Figure 18: Experiment 5. Target lightness in monocular and binocular conditions. Lightness of the left, lighted black target shown in black and lightness of the right, shadowed white target shown in white.

A repeated measures ANOVA with condition (binocular vs. monocular) as a between-subjects factor and target (left vs. right) as a within-subjects factor revealed a significant main effect of target, $F(1, 28) = 92.01$, $p < 0.001$. Overall, the left target, perceived coplanar with the lighted white side of the display but seen against the shadowed black side, appeared lighter ($M = 1.32$, $SE = 0.03$) than the right target, perceived coplanar with the shadowed black side of the display and seen against the lighted white side ($M = 0.85$, $SE = 0.04$). The ANOVA also revealed a significant main effect of condition, $F(1, 28) = 6.55$, $p < 0.02$. Overall, the perceived target lightness was lower in the monocular ($M = 1.02$, $SE = 0.04$) than in the binocular condition ($M = 1.15$, $SE = 0.04$). Finally, the ANOVA revealed a Target x Condition interaction, $F(1, 28) = 26.48$, $p < 0.001$ (see Figure 18), which was further explored in planned comparisons.

Paired *t*-tests revealed that the two targets differed in lightness within both the binocular ($t(19) = 2.53$, $p < 0.05$) and the monocular ($t(19) = 15.38$, $p < 0.001$) conditions, but the difference was in the opposite direction from that predicted by the coplanar ratio principle. The left target appeared lighter than the right target in both conditions, regardless of which plane it was perceived to be coplanar with.

An independent *t*-test showed that the change in lightness across conditions was marginally significant, $t(28) = -1.99$, $p = 0.056$. The right target however, appeared significantly darker when perceived as embedded (lying in the plane of, and completely surrounded by, the lighted background) than when it appears to float in front of it, coplanar with the shadowed side of the display, t(28) = 5.01, p < 0.001.

We compared Experiment 5 (the coplanar only condition) and Experiment 1 (the coplanar and adjacent condition) in a separate repeated-measures ANOVA with condition (binocular vs/ monocular) and experiment (1 vs. 5) as between-condition factors and target (upper/left vs. lower/right) as a within condition factor.

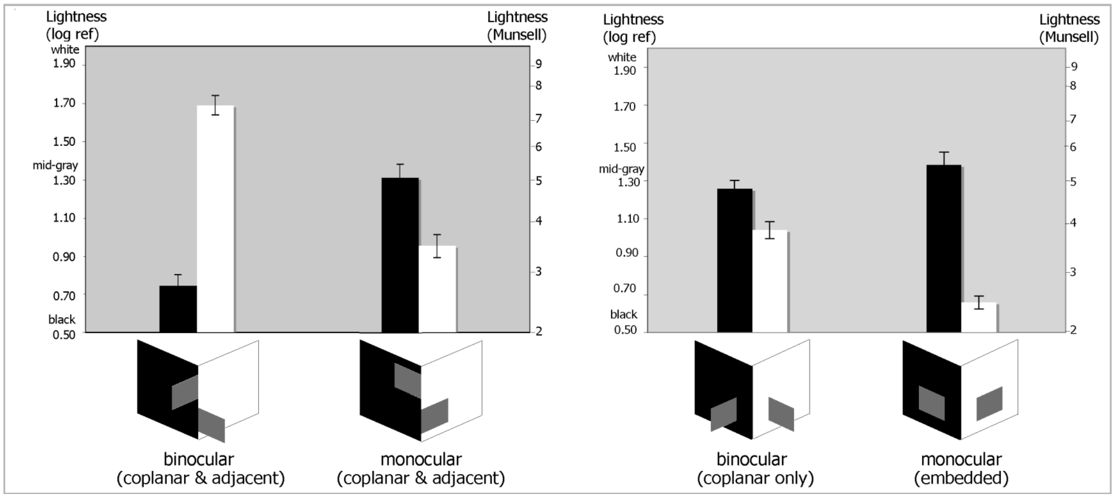

Figure 19: Comparison of results in Experiment 1 and 5. Mean target lightness in monocular and binocular conditions when they are both adjacent and coplanar with the sides of the display (Experiment 1, on the left) and when they are only coplanar but not adjacent (binocular condition, Experiment 5, on the right) or when they are embedded within a side of display (monocular condition Experiment 5, on the right). The lighted black target (upper/left) is shown in black and the shadowed white target (lower/right) shown in white.

The ANOVA revealed a significant main effect of condition, $F(1, 66) = 8.87$, $p < 0.01$, as well as experiment, $F(1, 66) = 6.29$, $p < 0.05$. Overall, the targets were perceived as darker in the monocular ($M = 1.08$, $SE = 0.03$) than in the binocular condition ($M = 1.18$, $SE = 0.03$). However, the source of this effect is in Experiment 5, as no main effect of condition is found in Experiment 1.

The ANOVA also revealed a significant main effect of experiment, $F(1, 66) = 6.29$, $p < 0.05$. Overall, the targets were perceived as darker in Experiment 1 ($M = 1.09$, $SE = 0.03$) than in Experiment 5 ($M = 1.17$, $SE = 0.02$). The ANOVA also revealed a Target x Experiment interaction, $F(1, 66) = 66.5$, $p < 0.001$. While in Experiment 1 the black target overall appeared darker than the equiluminant white target, in Experiment 5 it appeared lighter (see main effect of target in Experiment 1 and Experiment 4, respectively).

The ANOVA also revealed a Target x Condition interaction, $F(1, 66) = 92.74$, $p < 0.001$. Overall, black (upper/left) target appeared darker ($M = 1.00$, $SE = 0.04$) than the white (lower/right) target in the binocular condition ($M = 1.36$, $SE = 0.04$). However, in the monocular condition it appeared lighter ($M = 1.34$, $SE = 0.04$) than the white target ($M = 0.81$, $SE = 0.04$). It is important to note that this trend of change appears only when the matches are summed across experiments, while the trend within each of the two experiments is different. Therefore, Target x Condition interaction is analyzed and interpreted only within each experiment separately.

Finally, the ANOVA revealed a Target x Experiment x Condition interaction, $F(1, 66) = 17.9$, $p < 0.001$ (see Figure 19), which was further explored in planned comparisons. Independent *t*-tests compared each target in each condition across experiments. The upper/left target appeared significantly lighter in the binocular condition of Experiment 5 than in the same condition of Experiment 1 ($t(33) = 6.24$, $p < 0.001$), while the reverse was true for the other target ($t(33) = 6.60$, $p < 0.001$). In the monocular condition, the black target did not significantly differ in lightness across experiments. However, the lower/right target appeared significantly darker in the monocular condition of Experiment 5, than in the same condition of Experiment 1, $t(33) = 3.98$, $p < 0.001$.

Discussion

When the continuity within a plane was disrupted, the depth effect obtained in Experiment 1 disappeared. The two targets, perceived as coplanar with two different sides of the display, appeared different in lightness, but that difference was in the opposite direction of that predicted by the coplanar ratio principle (and obtained in Experiment 1). In the binocular condition, the target that appeared coplanar with the lighted side of the display appeared lighter, not darker than the equiluminant target that appeared coplanar with the shadowed side. Instead, the results suggest the influence of retinal ratios: in both conditions, the left target, retinally surrounded by the lighted side of the display, appeared darker than the equiluminant right target, surrounded by the shadowed side of the display.

However, comparison across conditions shows that target lightness is not only determined by retinal ratios, but that perceived coplanarity also plays a role. In both monocular and binocular conditions, the retinal ratios for both targets remain the same while the perceived depth of the targets changes. If target lightness were to depend only on retinal ratios, perceived lightness would not change across conditions. In fact, the left target did appear darker in lightness when it appeared to float in front of the shadowed black side of the display in the binocular condition compared to when it appeared to lie embedded in the middle of it in the monocular condition when the perceived planarity changed, but this difference was only marginally significant. However, the right target appeared significantly lighter when floating in front of the brightly illuminated side of the display in the binocular condition, than when it appeared to lie embedded in the middle of it in the monocular condition.

This darkening of the right target in the monocular (embedded) condition is consistent with findings on the insulation phenomenon (Gilchrist et al., 1999), described in the introduction. Completely surrounding the target by the coplanar and adjacent high-luminant background in the monocular (embedded) condition causes the insulation of the local framework with which the target is grouped, from the influence of the global framework. Due to this insulation, the target lightness is determined primarily based on the local computation. Given that the right target is thirty darker than its brightly illuminated coplanar surround, it will locally be assigned the value of black. Thus, it's perceived lightness will be near black.

In the binocular (the coplanar only) condition, when the target on the right is perceived to float in front of the high-luminance side of the display, the grouping of the target and its non-coplanar background will be weaker than in the embedded (the monocular) condition, when they are perceived to lie in the same plane. Thus, in the binocular condition the target is not completely insulated and its perceived lightness is co-determined both by its coplanar (though non-adjacent) neighbor and its retinal surround.

The finding that the perceived lightness of the target retinally surrounded by the high-luminance background changes as a function of perceived depth is in agreement with results obtained by Gilchrist and Radonjić (2007). They showed that, when the surround luminance is kept constant, the effect of insulation is bigger when the high-luminance surround lies in the same plane with a group of surfaces it is insulating, than when it lies behind it, in a different depth plane.

From the perspective of the anchoring theory, explaining how lightness is computed when the target is not adjacent to the coplanar side of the display, but appears to float in front of the non-coplanar side, requires the identification of the local framework the target is grouped with for the purpose of lightness computation.

One possibility is that in the absence of an adjacent coplanar surface, the target is locally grouped with the next deeper depth plane, as Kardos (1934) proposed. In Experiment 5, the effect of such a grouping, would be similar to that predicted based on the local contrast account. However, this grouping would be weaker than grouping based on coplanarity in the monocular condition. Thus, this hypothesis would predict a difference in target lightness between the two conditions because the retinal background would have less influence on target lightness in the binocular (grouping based on next deeper depth plane) than in the monocular condition (grouping based on coplanarity and adjacency). This prediction is supported by the general trend in the data.

Another possibility is implicit in the relaxed coplanar ratio principle (Gilchrist and Radonjić, 2006), according to which surfaces that are parallel and facing the same direction are grouped for lightness even if they are not immediately adjacent or coplanar. This would mean that the target is still locally grouped with the non-adjacent coplanar surface, but the strength of this grouping is much weaker than when the coplanar surface is adjacent; consequently the weight that such a local framework has in lightness computation would be smaller. However, the results inverse of the depth effect in the binocular condition suggest that in the absence of continuity within a plane, mere coplanarity, though playing some role, is not decisive.

Based on the results of Experiment 5 we can conclude that mere coplanarity is not a sufficient condition for grouping surfaces for lightness computation. The findings of He & Nakayama (1992, 1994), according to which the visual system prefers to make comparisons within a continuous group of surfaces, rather than across non-continuous surfaces in space, also seem to apply to lightness.

This makes logical sense: surfaces that lie within the same plane may or may not be equally illuminated. When the surfaces within a plane are adjacent, forming a continuous larger surface, any change in illumination would be signaled by a visible penumbra. When the coplanar surfaces are separated by a gap, it is possible that a penumbra falls within the gap. In other words, when the surfaces within the plane are continuous, more information about the fields of illumination to which these surfaces belong will be available to the visual system, based on which, the appropriate grouping for lightness computation can be determined.

Experiment 5A: Can surroundedness substitute for continuity within a plane in coplanar lightness computation?

If breaking the continuity within a plane weakens lightness computation based on coplanar ratios and enhances the computation based on retinal ratios, it is worth asking whether there is some spatial arrangement that, even in the absence of immediately adjacent surfaces, enhances grouping of non-adjacent surfaces within a plane, and consequently promotes coplanar lightness computation.

The work of Kardos (1934) as well as the replication of this work by Gilchrist and Todorović (unpublished study, as cited in Gilchrist, 2006), shows that such special spatial arrangement might be surroundedness.

Kardos (1934) measured the perceived lightness of a disk whose position in depth changed across conditions: it appeared either in the near plane, coplanar with a brightly illuminated hole-board (the near condition), or in the far plane, coplanar with a shadowed back wall (the far condition). Across conditions, retinal image of the disk was kept constant in both luminance and retinal size, however the perceived lightness changed: when the disk was seen in a plane of the hole-board, it appeared darker than when it was seen in the plane of the back wall. Kardos only described this effect qualitatively, but when Todorović and Gilchrist replicated the study they found that the change in perceived lightness of a disk, as a function of perceived position was as large as 4.4 Munsell units (as cited in Gilchrist, 2006). This result suggests that surroundedness within a plane may change the perceptual organization of the visual field for purposes of lightness computation.

The goal of Experiment 5A was to test whether surrounding the target with a coplanar but not adjacent surface can substitute for continuity within a plane or, in other words, if surroundedness can enhance coplanar grouping for lightness even when the surfaces are not adjacent. Each side of the display was extended, one at a time, creating a non-adjacent surround for each floating target.

To assess the effect of surroundedness, the lightness matches for each target in Experiment 5A (the coplanar & surrounded condition) were compared to those in the binocular condition of Experiment 5 (the coplanar only condition) and those in the binocular condition of Experiment 1 (the coplanar & adjacent condition).

If surroundedness does not have an effect on lightness, perceived target lightness will be computed based on retinal ratios, and the results will be the same in the surrounded & coplanar and the coplanar only condition. If surroundedness does have an effect, then target lightness will be different in the coplanar & surrounded and coplanar only conditions. Instead, target lightness in the coplanar & surrounded condition will be closer to that in the coplanar & adjacent condition.

Method

Experiment 5A was equivalent to Experiment 5 in all respects except that the display was modified so that a coplanar surround was added to each target, one at the time. In each condition, one side of the display was extended to create a 1.7 cm-wide border surrounding one of the floating targets. The border was in the shape of a square and its outer edge was equal to a side of the display (11 cm a side). The border looked like a paper hole-board with a square hole (8 cm on a side), in the middle of which the target appeared to float. In each condition, the border was equal in reflectance and illumination (thus, also luminance) to the side of the display from which it extended. In one condition (the bright surround condition) the brightly illuminated white border extended from the lighted side of the display and surrounded the floating target that was seen against the shadowed black background. In the other condition (the dim surround condition) the shadowed black border extended from the shadowed black side of the display and surrounded the floating target that was seen against the lighted white background (see Figure 20).

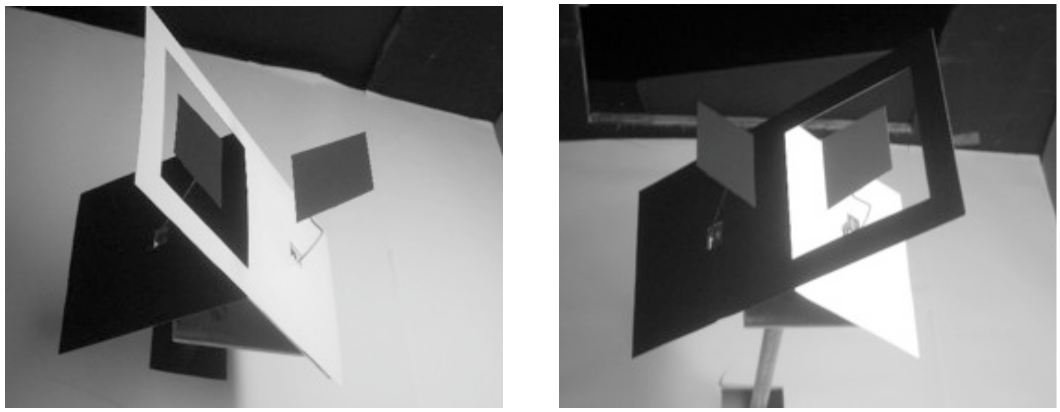

Figure 20. Stimulus set-up in Experiment 5A, view from the bottom in the bright surround (on the left) and in the dim surround condition (on the right); not equivalent to the observer's view.

A separate group of 15 observers viewed the display binocularly in each condition and judged the lightness of the surrounded target using a Munsell chart. One observer was excluded (and replaced) from the bright surround condition, as he was identified as an outlier.

Results

The mean lightness matches for the surrounded targets are plotted in Figure 21. The mean lightness matches from the coplanar & surrounded (binocular condition of Experiment 1) and the coplanar only condition (binocular condition of Experiment 5) are plotted for comparison.

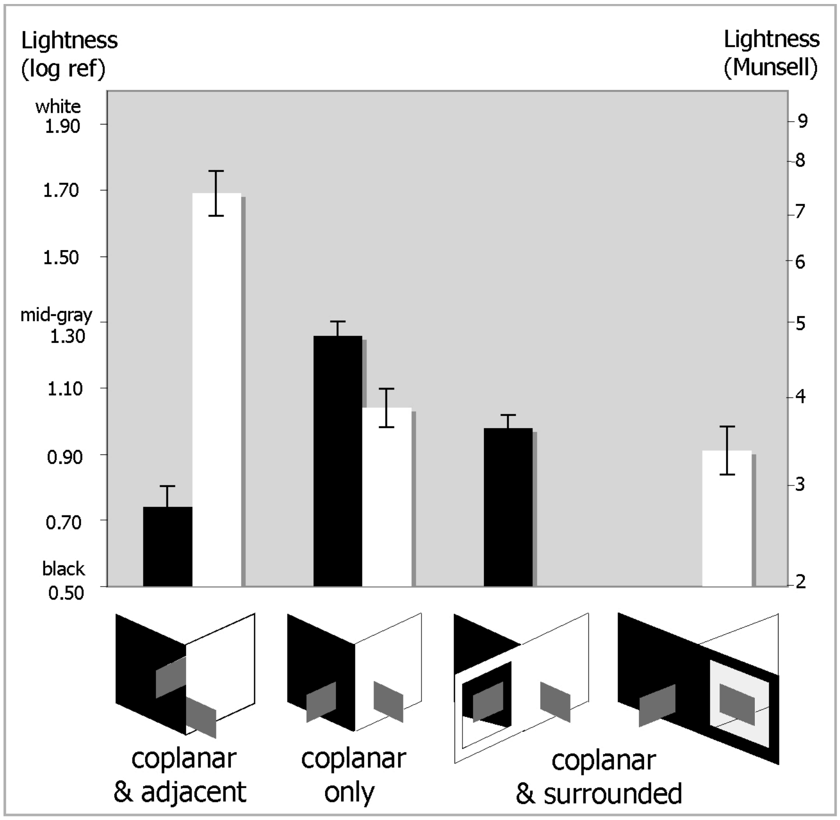

Figure 21: Experiment 5. Target lightness in the binocular condition of Experiments 1 (coplanar & adjacent), 5 (coplanar only) and 5A (coplanar & surrounded). Lightness of the left, lighted black target shown in black and lightness of the right, shadowed white target shown in white.

A repeated measures ANOVA with condition as a between-subjects factor and target as a within-subjects factor revealed a significant main effect of both target, $F(1, 47) = 14.13$ $p < 0.001$ and condition, $F(2, 47) = 13.28$ $p < 0.001$. Overall, the brightly illuminated black target was perceived as darker ($M = 0.99$, $SE = 0.03$) than the dimly illuminated white target ($M = 1.21$, $SE = 0.04$). Also, the targets appeared overall darker in surrounded & coplanar ($M = 0.94$, $SE = 0.04$) than in the coplanar & adjacent ($M = 1.22$, $SE = 0.04$) and coplanar only conditions ($M = 1.15$, $SE = 0.04$). The ANOVA also revealed a Target x Condition interaction, $F(2, 47) = 43.04$, $p < 0.001$ (see Figure 21). To further investigate this interaction, separate one-way ANOVAs compared the mean lightness values for each target across conditions.

The right, white target significantly varied in lightness across conditions, $F(2, 47) = 38.10$, $p < 0.001$. The Tukey HSD test showed that this target appeared significantly lighter in the coplanar & adjacent condition than in both the coplanar only ($p < 0.001$, consistent with the results of the Experiment 5) and the coplanar & surrounded condition ($p < 0.001$). However, the target did not appear different in the coplanar & surrounded condition, when compared to the coplanar only condition.

The lightness of the left, black target also significantly changed across conditions, $F(2, 47) = 22.25$, $p < 0.001$. The Tukey HSD test showed that this target appeared significantly darker in the coplanar & adjacent condition than in both the coplanar only condition, $p < 0.001$ and the coplanar and surrounded condition, $p = 0.01$. However, this target was perceived as significantly darker in the coplanar & surrounded condition than in the coplanar only condition, $p < 0.01$. Its mean lightness value in the coplanar & surrounded condition ($M = 0.98$, $SE = 0.05$) was half way between that in the coplanar & adjacent condition ($M = 0.74$, $SE = 0.06$) and that in the coplanar only condition ($M = 0.98$, $SE = 0.04$) on a log reflectance scale.

Discussion

The results show that surroundedness can substitute for continuity within a plane with two qualifications. First, the effect of surroundedness obtained in Experiment 5A was only half as big as the effect of continuity. Second, surroundedness was effective only when the target was surrounded with the brightly illuminated white border (the bright surround condition) and not when it was surrounded with the dimly illuminated black border (the dim surround condition).

The asymmetry reflected in the fact that only a high-luminance and not a low-luminance coplanar non-adjacent surround has an effect on target lightness is consistent with the insulation phenomenon described by Gilchrist et al. (1999). The dramatic compression of the lightness range produced when a row of five squares, covering the whole range of grays, is presented in the spotlight is negated by surrounding the squares with a white border (i.e. border equal to the highest luminance within the group), while surrounding the same group of surfaces with a lower luminance border does not have an effect (Gilchrist et al.,1999; Gilchrist, 2006).

The obtained results are also in agreement with those of Kardos (1934) and their replication by Gilchrist & Todorović described above. Interestingly, the luminance relations in their experimental set-up were equivalent to those in the bright surround condition: the non-adjacent coplanar hole board surrounding the target was white and in bright illumination, while the target retinal background was in black and in dim illumination. Had Gilchrist & Todorović tried to create inverse conditions, in which the retinal background was much higher and the surrounding border was much lower in luminance than the target, as in the dim surround condition it is likely that they would not have found the effect of surroundedness. It is worth noting that the effect Gilchrist & Todorović obtained was much larger than the effect obtained in the bright surround condition (4.4 vs. 1.9[34] Munsell units), though the experimental conditions were similar. There are three possible reasons for this difference.

(1) Given that the luminance range between the target and the surround in the Gilchrist and Todorović experiment was much larger than in Experiment 5 (86:1 vs. 30:1) or the nominal reflectance range, it is possible that the target was pushed to the bottom of the reflectance range, when compared for lightness with the coplanar, high-luminance surround in the near condition.

(2) The area of the surrounding hole-board in the Gilchrist & Todorović experiment was much larger, both in perceived and in retinal terms, than the area of the surrounding border in Experiment 5. According to the anchoring theory, the larger the local framework to which the target belongs, the more weight it has in the lightness computation. In the near condition, this would enhance the darkening of the target, which is locally assigned the value of black.

(3) Finally, it is possible that the perceived difference in lightness that Gilchrist & Todorović obtained is further enhanced by their articulation of the dimly illuminated black background. According to the anchoring theory, this would strengthen the local framework and increase the target lightness in the far condition, when the target appeared coplanar with the low-luminance background and is locally assigned the value of white.

In Experiment 5, both the lack of articulation of the background and relatively small size of the surround would weaken the local frameworks with which the target is grouped across conditions and thus reduce the size of the depth effect relative to Gilchrist and Todorović.

[34] The difference in lightness of the left target when it appears coplanar with the bright surround (the bright surround condition in Experiment 5A; binocular viewing) and when it appears coplanar with its shadowed retinal background (monocular condition in Experiment 5).

Further research is required to explore why only the high-luminance and not the low-luminance surround enhances grouping for lightness within a plane. However, the findings of Experiment 5A together with those of Kardos (1934) and Gilchrist & Todorović emphasize the empirical fact, consistent with the basic premise of the anchoring theory, that the highest luminance within an image is treated as special by the visual system.

Experiment 6: The role of luminance range in the depth effect on lightness

In its original formulation, one of the conditions for the coplanar ratio principle to apply is that the luminance range within an image needs to be substantially larger than 30:1. This requirement is based on the empirical findings of Gilchrist (1980) as well as many others (Hochberg & Beck, 1954; Beck, 1965; Gogel & Mershon, 1969; Coren, 1969; Flock & Freedberg, 1970), who found that when the luminance range in the display does not exceed 30:1, the depth has little or no effect on lightness. Furthermore, as discussed in the introduction, the luminance range constraint is supported by the logical assumption that the coplanar ratio principle should apply only when there are multiple fields of the illumination in the image: when the luminance range is 30:1, equivalent to the possible reflectance range, it is plausible for the visual system to interpret all luminance variations in the image as variations in reflectance under uniform illumination. Therefore, a luminance range larger than 30:1 may serve as a signal to the visual system that a scene consists of multiple fields of illumination. In such case, constraining the computation of surface lightness to only those values within a plane yields a more accurate lightness estimate, given that the surfaces within the same plane are usually equally illuminated.

However, the luminance range constraint of the coplanar ratio principle can be criticized for a lack of precision, as it does not specify how large the luminance range must be for depth to have an effect on lightness.

Empirical evidence suggests that the optimal luminance range for an effect of depth on lightness might be around 900:1 (Gilchrist, 1980). This is the luminance range used in both the parallel planes and perpendicular planes studies of Gilchrist (1977, 1980), replications by Schirillo et al. (1990) and a version of the Gilchrist et al. (1998) replication of Zaidi et al. (1997) study in which large depth effect on lightness were obtained. However, it is possible to find multiple fields of illumination in the image even if the luminance range in the image is much smaller than 900:1. Practically, as soon as the luminance range exceeds 30:1, "somewhere in the scene a white surface receives more illumination than some black surface" (Gilchrist, 1980, p. 534) and computing lightness based on coplanar rather than retinal ratios would yield more accurate lightness judgments. Therefore, theoretically, if the role of the luminance range is to signal the presence of multiple fields of illumination in the image, depth should have some effect on lightness in any image in which the luminance range is larger than 30:1.

The analysis of the previous studies also suggests that the size of the depth effect might depend on the size of the luminance range. Gilchrist obtained the depth effect of 5.5 Munsell units in the parallel planes study in which the luminance range was 2167: 1, but 4.25 and 4.75 Munsell units in the perpendicular planes study (1977, 1980) in which the luminance range was 900:1. Also, Schirillo et al. (1990) obtained a slightly larger depth effect with 2000:1 than with a 900:1 luminance range in their parallel planes replication (2.5 vs. 2 Munsell units). As the range in the display gets smaller than 900:1, the probability of getting an effect of depth on lightness becomes progressively smaller: Howe (2006) finds an effect as small as 1 Munsell unit when the luminance range is 236:1, but no significant effect with a 61:1 range. Zaidi failed to find the depth effect using luminance range of 85:1 and so did Dalby et al. (1995) using a luminance range of 1.2:1. However, because these studies differ in numerous aspects of experimental setup and design, it is not possible to draw reliable conclusions about the role of the luminance range on the depth effect based on this comparison.

In order to systematically explore (1) if depth has an effect on lightness when the luminance range in the image is less than 900:1 and (2) if the size of the depth effect depends on the size of the luminance range, in Experiment 6 the luminance range in the perpendicular planes display from Experiment 1 was systematically varied, by varying the reflectance of the shadowed side of the display (equivalent to the lowest luminance in the image).

Note that such an experimental design also allows testing of the differing predictions of the coplanar ratio principle and the anchoring theory about the role of the luminance range in the depth effect. According to the coplanar ratio principle, a large luminance range in the image is necessary for depth to have the effect on lightness; thus it is plausible to assume that varying the luminance range in the image will affect the size of both the between-condition and the within-condition depth effect. As suggested by Gilchrist (1980), an overall range substantially greater than 30:1 is necessary for an effect of depth on lightness.

However, according to the anchoring theory, target lightness and consequently the depth effect, does not depend on the luminance range. Remember that, according to the anchoring theory, the two targets appear different in lightness because the two planes to which they belong have different highest luminance values. Changing the lowest luminance in the shadowed plane will not change the local value for the target in this plane, which will still be the highest luminance in its local framework and locally assigned the value of white. As this does not change either the highest luminance in the lighted plane or the highest luminance in the global framework, the anchoring theory would not predict any change in target lightness or the depth effect across different luminance ranges.

Method

Experiment 6 was identical to Experiment 1 in all respects except the reflectance of the paper covering the shadowed side of the display was varied. Four different reflectance values, yielding four different luminance ranges conditions were used: (1) 3% reflectance (black Color-aid paper), yielding the luminance range of 30:1 (equivalent to Experiment 1); (2) 24.6% reflectance (Color-aid paper 4.5), yielding the luminance range of 110: 1, (3) 50.7% reflectance (Color-aid paper 7.5) yielding the luminance range of 53:1 and (4) 90% reflectance (white Color-aid paper, reflectance 90%), yielding the luminance range of 90: 1.

Initially, only three different reflectance values were chosen (black, white and middle gray) representing the lowest, the highest and the middle values on the reflectance scale. However, the matches and comments of observers indicated a considerable ambiguity in the perceptual organization of the stimulus in the 30:1 condition, when both sides of the display were white. In this condition the targets and the shadowed side of the display were equiluminant and thus not clearly distinguishable from each other. This caused large variations in observer's matches for the target perceived coplanar to the shadowed side of the display, so the results obtained in this condition could be considered uninformative due to high variability. In order to have a reliable measure of the effect of low luminance range, a condition in which the shadowed side of the display was covered with the light gray paper was included in the experiment. The chosen shade of light gray was the lightest Color-aid shade which, when mounted on the display, appeared clearly different in brightness from the targets.

The luminance of the targets was 17.6 cd/m^2 (up to 4% variation across condition, equivalent to the measuring error). The luminance of the lighted side of the display was 528 cd/m^2. The luminance of the shadowed side of the display was 0.59 cd/m^2 in the 900:1 condition (Experiment 1), 4.84 cd/m^2 in the 110:1 condition, 10 cd/m^2 in the 53:1 condition and 17.6 cd/m^2 in the 30:1 condition.

A separate group of 15 observers viewed the display in each of the monocular and binocular conditions for the middle gray-white, the light gray-white, and the white-white stimuli. Data from the two separate groups of 20 observers that viewed the display in the binocular and monocular conditions of Experiment 1, equivalent to the black-white condition, were included for comparison, yielding a total of 8 experimental conditions (4 luminance ranges x 2 viewing conditions). Based on the exclusion criteria 1 observers was excluded and replaced in three conditions (middle gray-white binocular, middle gray-white monocular and light gray-white monocular), as they were identified as outliers.[35]

Results

Mean lightness matches for each target across four different luminance range conditions are shown in Figure 22 in the binocular and the monocular condition.

[35]For observers excluded from the 900: 1 condition see Experiment 1.

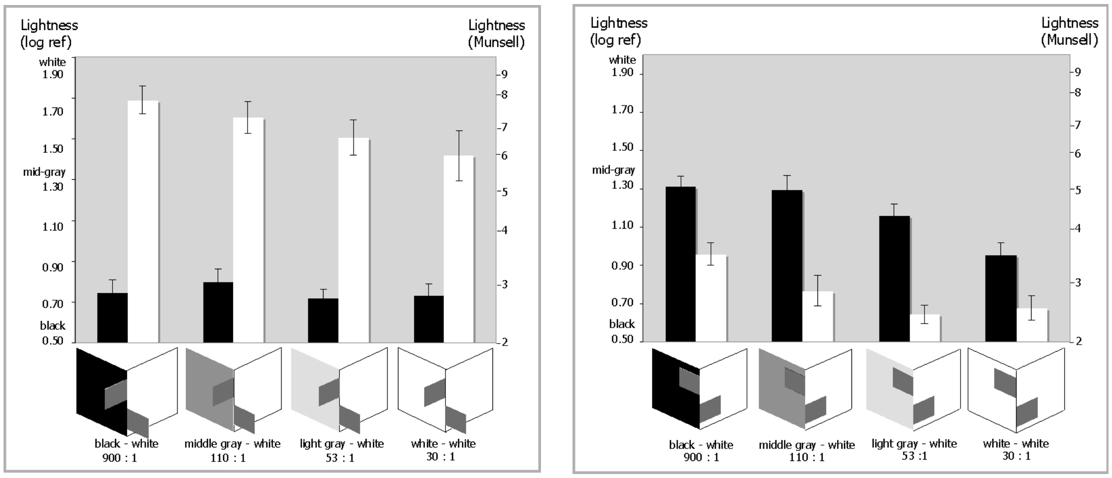

Figure 22: Experiment 6. Target lightness across four different luminance range conditions when viewed binocularly (left graph) and monocularly (right graph). Lightness of the upper, black target is shown in black and lightness of the lower, white target is shown in white.

Overall, the target appeared darker in the monocular (M = 0.97, SE = 0.02) than in the binocular condition (M = 1.15, SE = 0.02). Also, the upper target appeared overall darker (M = 0.96, SE = 0.02) than the lower target (M = 1.16, SE = 0.03), like in Experiment 1. Finally, there was an overall darkening trend as the luminance range got smaller: the targets were perceived the lightest in the 900: 1 condition (M = 1.17, SE = 0.03), somewhat darker in the 110:1 condition (M = 1.11, SE = 0.03), and the 53: 1 condition (M = 1.01, SE = 0.03) while they were perceived as darkest in the 30:1 condition (M = 0.94, SE = 0.03).

The ANOVA also revealed a significant Target x Viewing Condition interaction, $F(1, 122) = 23.91$, $p < 0.001$, which was further explored by planned comparisons. As in Experiment 1, paired t-tests revealed that the target that appeared coplanar with the lighted side of the display was perceived as significantly darker than the target that appeared coplanar with the shadowed side of the display in both binocular ($t(64) = 13.50$,

$p < 0.001$) and monocular ($t(64) = 9.51$, $p = 0.001$) conditions. Also, like in Experiment 1, independent *t*-tests revealed that the perceived lightness of each target varied as a function of the plane to which it was perceived to belong. The lower target appeared significantly lighter when perceived as coplanar with the shadowed side of the display in the binocular condition, than when perceived as coplanar to the lighted side of the display in the monocular condition, $t(38) = 13.84$, $p < 0.001$. The upper target appeared significantly darker when perceived as coplanar to the lighted side of the display in the binocular condition, than when perceived coplanar to the shadowed side of the display in the monocular condition, $t(38) = 8.16$, $p < 0.001$.

To explore the change in target lightness with the change in perceived depth, four separate 2 x 2 ANOVAs, with target as a within-subject and a viewing condition as a between-subject factor were conducted for each luminance range condition. They all revealed a Target x Viewing Condition interaction within each luminance range condition, replicating the direction of the overall interaction. Within each luminance range, the two targets differed significantly in lightness ($p < 0.001$ for all t values) and the targets significantly changed in lightness when the plane to which they were perceived to belong changed ($p < 0.001$, except upper target in the low range condition: $p < 0.02$).[36]

To explore further the effect of the luminance range on the depth effect on lightness, the size of both the between-condition and within-condition depth effects across the four luminance range conditions was compared using two separate 2 x 4 ANOVAs. The ANOVA for the between condition depth effect, with target and

[36]For complete results of the statistical analysis see Appendix II.

luminance range as between-subject factors revealed a significant main effect of target ($F(1, 122) = 27.19$, $p < 0.001$), replicating the overall main effect of target, but no main effect of the luminance range or the Target x Luminance Range interaction. The ANOVA for the within-condition depth effect, with condition and luminance range as between-subject factors revealed a significant main effect of condition, $F(1, 122) = 27.19$, $p < 0.001$, replicating the overall main effect of condition, but no main effect of luminance range or the Condition x Luminance Range interaction.

	Depth effect in log reflectance (Munsell)			
Luminance range	Within condition		Between condition	
	Binocular	Monocular	Upper target	Lower target
900: 1	0.94 (4.8)	0.35 (4.00)	0.56 (2.4)	0.73 (4.00)
110:1	0.81 (4.0)	0.53 (4.51)	0.49 (2.2)	0.84 (4.10)
53:1	0.79 (3.7)	0.51 (3.97)	0.44 (1.7)	0.86 (3.97)
30:1	0.68 (3.4)	0.27 (3.53)	0.22 (0.8)	0.74 (3.53)

Table 1: Experiment 6. Mean size of the within-condition and the between-condition depth effects across four luminance ranges (in log reflectance and Munsell equivalent).

Despite what appears to be a trend indicating that the within-condition depth effect decreased with the decrease in the luminance range in the binocular condition (see Table 1), the ANOVA did not reveal any significant difference in the size of the within condition depth effect in either the binocular or the monocular condition; also, Tukey HSD tests do not show a significant difference between any two luminance range conditions in either binocular or monocular viewing.

For the between-condition depth effect the ANOVA shows that the change in lightness with the change in perceived depth varies significantly across different luminance range conditions, but only for the upper (F (3, 64) = 2.88, $p < 0.05$), and not for the lower target ($F < 1$, *ns*). Tukey HSD tests show that for the upper target the change in lightness with the change in perceived depth was significantly smaller in the 30:1 than in the 900:1 condition ($p < 0.05$), while between-condition depth effects at all other luminance ranges did not significantly differ.

Discussion

The basic depth effect on lightness found in Experiment 1 was replicated. Across all luminance range and viewing conditions the target that appeared coplanar with the shadowed side of the display was always perceived as lighter than the target that appeared coplanar to the shadowed side of the display. Also, within each luminance range condition, the change in perceived position of the target with the change in viewing conditions was accompanied by a change in target lightness.

The results suggest that, consistent with the predictions of the anchoring theory, but contrary to the predictions of the coplanar ratio principle, the luminance range does not necessarily affect the depth effect. Even when the size of the luminance range in the image is as small as 30:1, the target lightness changes as a function of the perceived depth. Furthermore the size of either the between-condition or the within-condition depth effect does not change significantly when the luminance range in the image varies from 900:1 to 53:1.

The large variability, as well as the reports of the observers suggest that when the luminance range was 30:1 the stimulus that was used was perceptually ambiguous.

Similar to the Mach bent-card illusion the two sides of the stimulus could be perceived as either being equal in reflectance but differently illuminated, or as being different in reflectance, but equally illuminated.

In the first case the target perceived as coplanar to the shadowed side of the display would be perceived as white or light gray in the shadow, while in the second case it would be perceived as dark gray or black in bright illumination. Note that this perceptual ambiguity would affect only the target coplanar with the shadowed side of the display and not the target coplanar with the lighted side of the display, which, thirty times darker than its coplanar highest luminance will always be perceived as dark gray or nearly black. It is unclear however why the variability is high for the target coplanar to the shadowed side only in the binocular and not the monocular condition, when it is perceived as dark gray. However, this may reflect the main effect of target, showing that overall the black target appears darker than the white target consistently across experiments.[37]

In general, these results are consistent with those of Gilchrist (1980) who pointed out the ambiguity in the perception of reflectance and illumination in stimuli with a limited range of luminance. However, at the same time they bring into question the validity of the luminance range constraint: for some observers, the target coplanar to the shadowed side of the display in the binocular condition appeared light gray or white, thus significantly lighter than for the observers in the monocular condition. Therefore based on these results one cannot conclude that when the luminance range in the image is limited to 30:1 depth does not have an effect on lightness.

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[37]For some possible explanations of this effect, see the discussion section of Experiment 1.

Experiment 6A: Can depth affect lightness if the luminance range in the stimulus is 30:1?

In order to get a clear answer to the question of whether depth affects lightness when the luminance range in the stimulus is as small as 30:1, one would first need to create experimental conditions that are not perceptually ambiguous.

One possible reason for the variability recorded in white-white condition of Experiment 6 may be that the stimulus that was used was too simplified. Rarely in everyday life would one encounter two homogenous surfaces of different luminance so isolated from any contextual cues that proper attribution of reflectance and illumination is ambiguous. Instead, scenes in the real world are often richly articulated, providing sufficient information to the visual system to estimate surface reflectance and illumination.

In order to make the display less ambiguous, the sides of the display were articulated, but in such a way that the limited 30:1 range in the display was preserved: one side of the display consisted of gray shades darker than or equal to middle gray, while the other side consisted of gray shades lighter than or equal to middle gray.

The lightness of the target extending from the dark gray side of the display was measured while its perceived position changed with the change of viewing conditions. When viewed binocularly, the target appeared veridically in depth: coplanar with the dark-gray side of the display. When viewed monocularly, the target, trimmed to conform to its immediate retinal background appeared coplanar with the light-gray side of the display (see Figure 23).

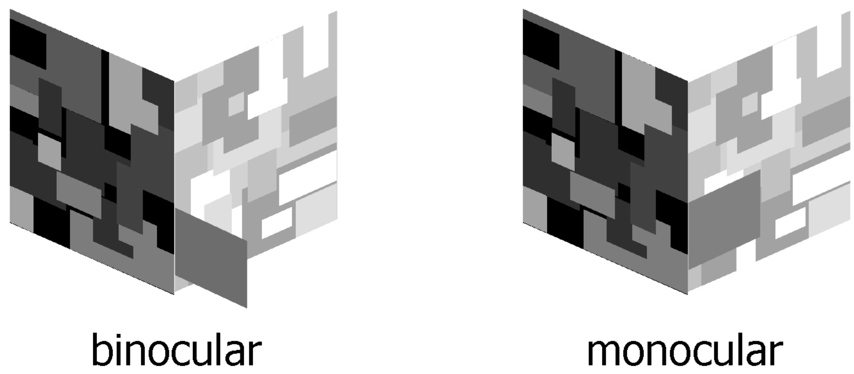

*Figure 23:*A perspective view that illustrates the perceived spatial arrangement (not the observers' retinal image) in the binocular and monocular conditions, when one side of the display consists of only dark gray and the other of only light gray shades (actual target position did not change). The gray shade used to depict the target has been darkened slightly just for visibility.

If depth does not affect lightness when the range in the stimulus is 30:1, then the target lightness will not change with the change in perceived position. In other words, the between-condition depth effect will be close to 0. If depth affects lightness even when the range is as small as 30:1, then the target will change in lightness when its perceived position changes and the between-condition depth effect will be greater than 0.

Method

Experiment 6A was identical to the Experiment 1 in all respects except for the following differences.

(1) Each side of the dihedral corner was replaced with a mondrian pattern, consisting of patches of 5 different reflectance (4-5 patches of each reflectance, yielding approximately 20 patches a side) covering half of the reflectance range on a log reflectance scale. The left side of the display was covered with a mondrian pattern

consisting only of dark-gray shades, ranging from 3% to 15.6% reflectance (Color aid black, 1.5, 2, 2.5. 3.5). The right side of the display was covered with the mondrian pattern consisting of only light-gray shades, ranging from 15.6% to 90% reflectance (Color aid 3.5, 5.5. 7.5, 8.5 and white). The structure of the pattern was pseudorandom and approximately the same for both sides. The grouping of dark-gray and light-gray shades on each side was such that it simulated an illumination difference of approximately 6:1, measured as the ratio between the highest luminance on each side of the display.

(2) The display contained only one target. The target was middle gray (3.5 Color-aid paper, reflectance 15.6%), chosen so it represents the middle on the log reflectance scale: it was equivalent in reflectance to the lightest shade on the dark-gray mondrian and to the darkest shade on the light-gray mondrian. It was identical in shape, size and position to the lower target in Experiment 1, extending from the left side of the display.

(3) Two sides of the display were equally illuminated, each by a 75W incandescent bulb, positioned outside of the vision tunnel, 20 cm from each side-wall, supported by a stand at 120 cm height and at 47 cm diagonal distance from the side of the display it was illuminating. The beam of each bulb passed through one of the square apertures on the sidewalls of the tunnel (see Figure 24).

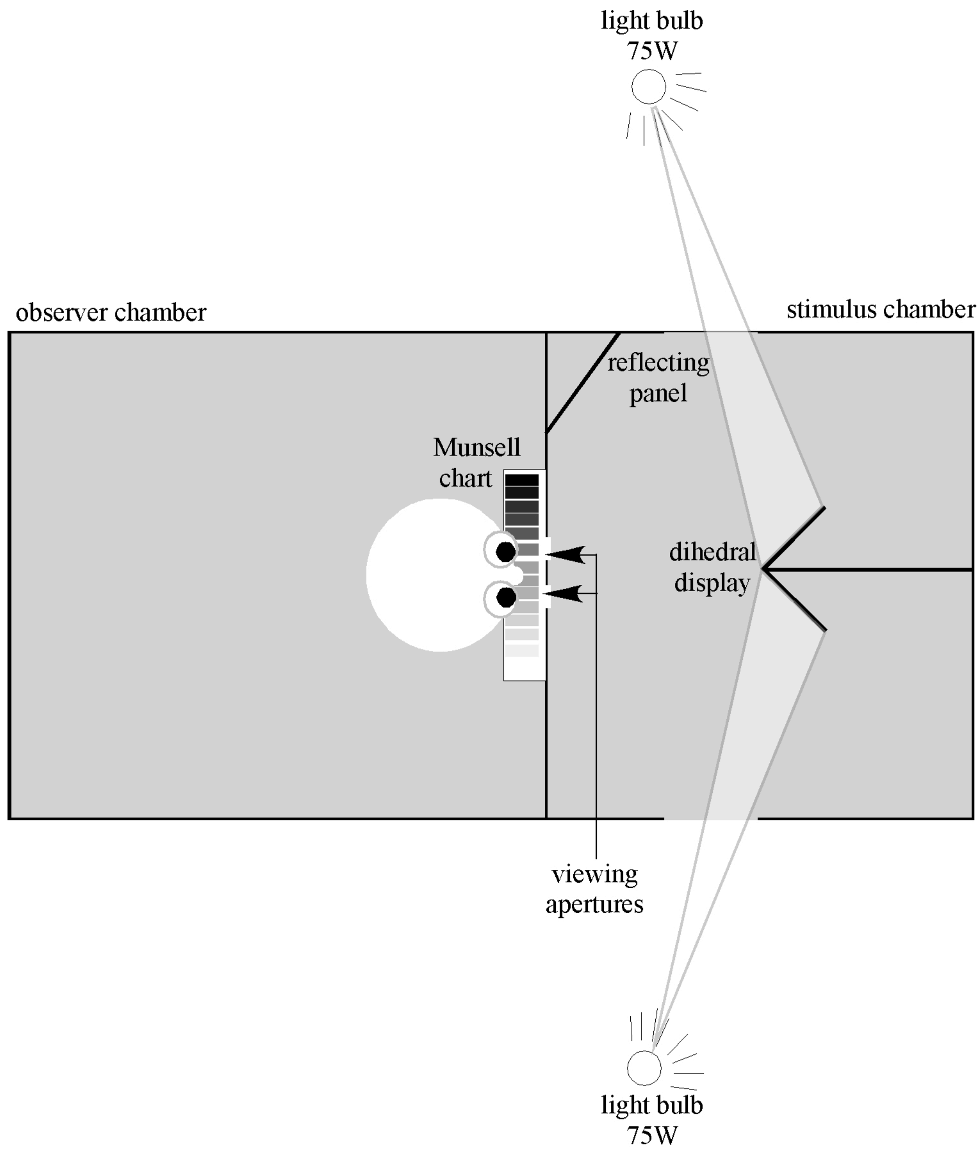

Figure 24: Plan view of the experimental apparatus in Experiment 6A (drawn to scale).

Proximal stimulus. The luminance of the target was 17.3 cd/m^2. In the light side of the display, the luminance of the highest luminance patch (white) and the lowest luminance patch were 90.3 cd/m^2, and 15.6 cd/m^2, respectively; in the dark side of the display they were 17.6 cd/m^2 and 3.76 cd/m^2. The luminance of the white background (in the brightest part) was 74.2 cd/m^2.

Observers. A separate group of 15 observers matched the target lightness in the binocular and monocular conditions using a Munsell scale.

Results

Mean lightness matches for the target in the binocular and the monocular conditions are shown in Figure 25.

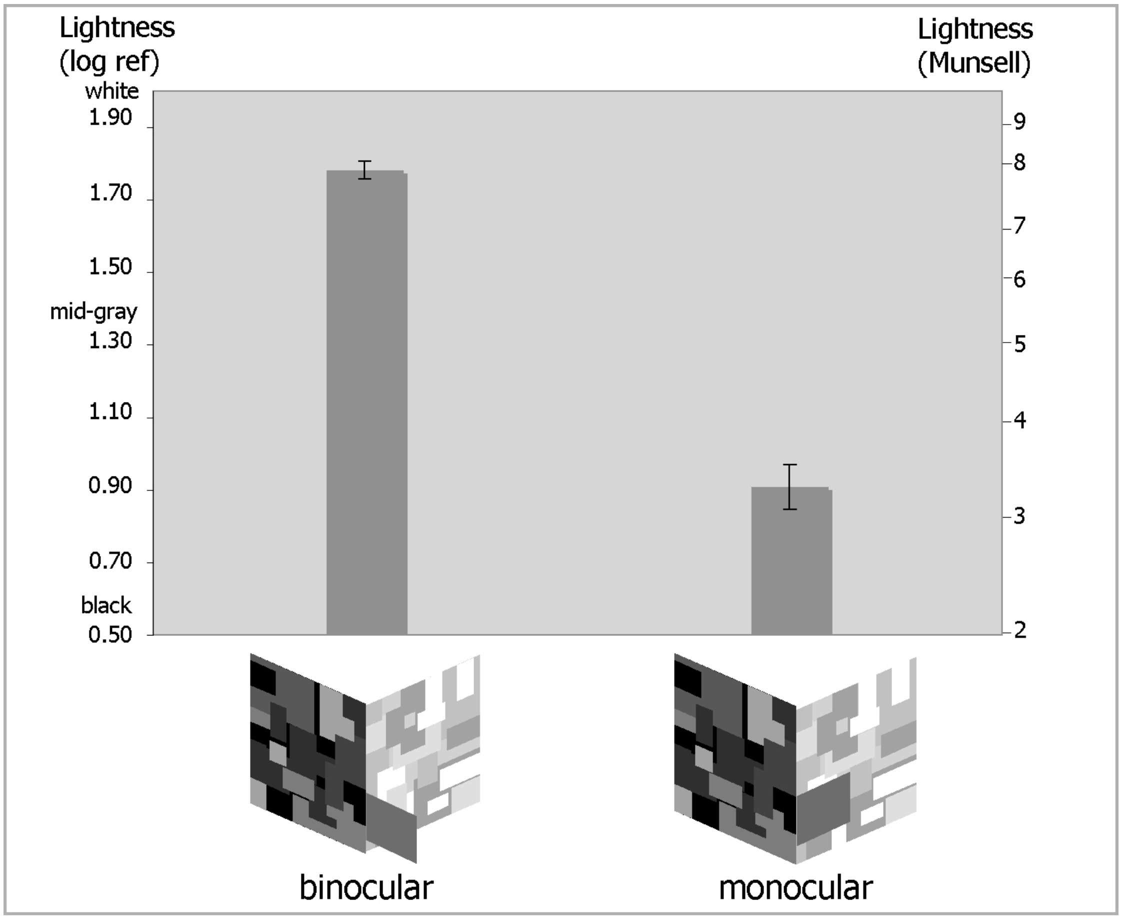

Figure 25: Experiment 6A. Target lightness in the monocular and binocular conditions.

The target lightness in the binocular and monocular conditions was compared using independent *t*-test which revealed a significant difference in target lightness across conditions, $t(28) = 13.07$, $p < 0.001$. The between-condition depth effect yielded 0.87 log reflectance (equivalent to 4.7 Munsell units).

Discussion

The results show that when the sides of the display are articulated, even when the luminance range in the stimulus is 30:1, perceived depth does have a significant and substantial effect on lightness. When it was perceived coplanar with the dark-gray mondrian in the binocular condition, middle gray target appeared light gray (Munsell 8.1). By contrast, when it was perceived coplanar with the light-gray mondrian in the monocular condition, it appeared dark gray (Munsell 3.4).

These results are generally consistent with the results of Schirillo and Shevell (1993) who found a depth effect on both lightness and brightness when the luminance range in the display is limited to 30:1, but the illumination difference is simulated using truncated light-gray and dark-gray range in the two planes, as in Experiment 6A. However, the effect they obtained was much smaller: only 17% increase in test luminance averaged across 4 different luminance/simulated reflectance values. One reason for the small effect is certainly related to the fact that in their experiment, in one condition the target appeared coplanar to the non-retinally adjacent surface - floating in the same plane, but not immediately adjacent to it. As the results of Experiment 5 show, when the surface is not a part of continual group of surfaces within a plane, depth effect on lightness will be very small or not significant.

Note that the results of Experiment 6A are also consistent with the prediction of the anchoring theory that the target will change in lightness when it moves from one plane to another if the different planes have different highest luminance (see discussion of Experiment 4). However the depth effect is greater than would be predicted by the anchoring model.

The stimulus in Experiment 6A simulated a 6:1 illumination difference, given the 6:1 difference in the highest luminance values in the two planes. Nevertheless target lightness changed by a factor of 7.4:1 as it moved from one plane to the other. This is a substantial over-constancy that remains to be explained. The co-determination principle that lies at the heart of the anchoring theory constitutes an explanation of under-constancy, which is the standard finding. Furthermore, when the absolute size of the effect is compared, the depth effect in Experiment 6A was larger and not smaller than that obtained in Experiment 2 (0.87 vs. 0.84 log reflectance, 4.7 vs. 4.2 Munsell units). This is a major contradiction of the luminance range constraint in the coplanar ratio model.

General discussion

Overall, the results show a remarkable consistency of the depth effect on lightness across various experimental conditions using the perpendicular planes setup and they are generally consistent with numerous recent studies showing that the perceived three-dimensional arrangement plays a significant role in lightness computation (Knill & Kersten, 1991; Logvinenko & Meshnikova, 1994; Spehar et al., 1995; Taya et al., 1995; Pessoa, Mingolla & Arend, 1996; Bloj, Kersten & Hurlbert, 1999; Boyaci et al., 2003, 2006; Ripamonti et al., 2004; Bloj et al., 2004).

The results in the light of the anchoring theory

The analysis of results across experiments suggests that the anchoring theory provides a theoretical framework that can account for the majority of the findings.

Contrary to the coplanar ratio principle, the anchoring theory can account for (1) underconstancy of target lightness under a change of plane (Experiment 1), (2) articulation effects on target lightness and consequently the depth effect when the coplanar adjacent luminance does not change (Experiment 2), (3) the absence of a change in target lightness and the depth effect when the adjacent coplanar luminance changes but the coplanar highest luminance remains the same (Experiment 3) and finally, (4) the absence of an effect of luminance range on the depth effect on lightness (Experiment 6).

In addition, when compared to the coplanar ratio principle, the anchoring theory has an epistemological advantage because it proposes a more general mechanism that the visual system might use to compute lightness in complex three-dimensional scenes, of which the perpendicular planes experimental setup is only one example. Lightness computation in perpendicular planes displays can be understood as a case of computation when frameworks in the image are segregated based on planarity. In such a context, when the manipulation of spatial and photometric factors across experiments causes lightness changes, this can be interpreted as a change in grouping i.e. segregation of frameworks for lightness computation.

The manipulation of photometric factors in Experiment 6 and 6A suggests that a large luminance range is not required for an effect of depth on lightness, at least when the planes in the image are articulated. Together with the results of Experiment 2, these results suggest that articulation has an effect on lightness that may be closely related to framework segregation. In addition to strengthening individual frameworks directly it is possible that articulation may affect framework strength indirectly, by increasing the segregation between frameworks. This interpretation of the role of articulation may explain both the results of Experiment 2, in which articulation has an effect only in the monocular condition when conflicting depth cues can make frameworks in the image less segregated, but not in the binocular condition when the frameworks are well segregated. It can also account for the results of Experiment 2A showing that the articulation of any side of the display has an effect on lightness, because the articulation of any side would strengthen the framework segregation.

The manipulation of spatial factors in Experiment 5 suggests that coplanar grouping for lightness is strongly dependent on continuity within a plane. When the surface appears to float in space, isolated from other surfaces in the same plane, the depth effect disappears, suggesting that the grouping of non-continuous surfaces for lightness dramatically weakens. Note that on a theoretical level, grouping surfaces for lightness is efficient in estimating target lightness only when the surfaces that are grouped together are those that are equally illuminated in the environment. When coplanar surfaces form a continuous larger surface then any spatial change in illumination will be signaled by a visible penumbra, but when they are separated by a gap it is possible that a penumbra will fall within this gap. In other words, when the surfaces are separated by a gap, there is not enough information within an image to signal whether the coplanar non-contiguous surfaces belong to the same field or different fields of illumination, so the grouping for lightness is weaker than when the surfaces are continuous in space.

The results of Experiment 5A suggest that when a surface floating in space is completely surrounded by a coplanar but not-adjacent border, the coplanar grouping is stronger than when the target is floating isolated in a plane, but weaker than when the target is part of a continual group of surfaces like in Experiment 1, 2 or 3. When the target is completely surrounded in space by another surface, which is coplanar but not adjacent, a penumbra could fall within this gap, but this would be highly coincidental. In other words, a comparison of the results of Experiment 5, 2 and 3 suggests that the strength of grouping surfaces for lightness computation corresponds to the probability with which it is possible to estimate the illumination conditions across space. It remains unexplained however, why only the high-luminance and not the low-luminance surround enhances grouping for lightness of non-coplanar surfaces within a plane. This finding is consistent with other findings that have been labeled insulation: when patches in the brighter illumination are surrounded by a border of the highest luminance, they seem to be immune to influences from an adjacent framework i.e. co-determination (Kardos, 1934). But the logical account for such an insulation effect is not clear.

The results in the light of low-level theories

The results obtained across experiments represent a challenge for low-level theories of lightness that emphasize retinal processes such as lateral inhibition (Cornsweet, 1970; Hurvich & Jamison, 1964) in lightness computation, but also for more sophisticated filtering models such as the ODOG model of Blakeslee & McCourt (1999, 2003) or model of Robinson et al. (2007), according to which lightness (brightness) perception is the result of a computation performed by a multiscale scale array of oriented two-dimensional difference-of-Gaussian filters that operate across the retinal image. Any mechanism based solely on the retinal image necessarily fails to account for changes in lightness that occur when spatial arrangement is varied while the retinal image is kept constant. In other words, low-level retinal models are indifferent to any change in depth that is not reflected in the retinal image.

Furthermore, theories emphasizing the importance of local contrast in lightness computation cannot account for the change in lightness with a change of articulation when the local contrast remains the same (Experiment 2) or for the absence of change in lightness when the local contrast changes (Experiment 3). Even if some of these findings can be explained by multiscale filtering accounts, because articulation can change the filter output at a certain scale, explaining the differential effect of articulation across the viewing conditions obtained in Experiment 2 remains problematic for filtering models.

New inverse optics models of lightness computation in complex three-dimensional scenes

Recently, an effect of spatial position on lightness has been studied by Maloney and his collaborators using computer simulated stereo-displays (Boyaci et al., 2003, 2004, 2006) as well as by Brainard and his collaborators using real paper-and-illuminant displays (Ripamonti et al., 2004; Bloj et al., 2004). The research of both labs showed that perceived target lightness changes as a function of the perceived orientation relative to the light source, but substantial individual differences in lightness matches were found. To explain the obtained results both labs developed models based on the inverse optics logic according to which the visual system estimates the illumination in a scene and then discounts it to obtain the estimate of surface lightness.

According to Boyaci et al. (2006), lightness judgment is a two-step process. In the first step the observer first construes an Equivalent Lightning Model (ELM) of the spectral and spatial distribution of illumination which contains information about the position, relative intensity and the spectral composition of the light sources in a given scene. Such a model is construed based on the cues available in the image, such as cast and attached shadows (Boyaci et al., 2006) and specular highlights (Boyaci et al., 2006, Yang & Maloney, 2001) in a process of weighted cue combination based on an internal assessment of their efficiency, i.e. relative informational value in a given situation (Maloney, 2002). In the second step the illumination is discounted by relying on a geometric correction factor based on the observers ELM.

According to this type of model, errors in lightness constancy are correlated with the errors in estimation of two parameters of the model - position and relative intensity of the light source(s) in a given scene: to the extent to which the observer estimates these two parameters correctly, his/hers lightness matches will be constant (Bloj et al., 2004). Such a model has the advantage of being able to account for large individual differences between observers, who may be more or less accurate in the ELM estimate, due to reliance on one type of illumination cues rather than another (Boyaci et al., 2006). A possible disadvantage of this type of model, however, is that it assumes a quite complex computational process. If, as noted by Boyaci et al. “it is not plausible to expect that any biological visual system performs any visual task optimally” (Boyaci et al., 2006, p. 115), than the system seems to perform a very complex computation in order to achieve only approximately correct outcome. If this is the case, a better solution might be an alternative principle that would yield an equally effective output with a less complex computation.

Such a principle is proposed by Gilchrist and Radonjić (2006, also manuscript in preparation) who argue that the results obtained by the Brainard and Maloney labs can be more simply explained by a variant of Gilchrist’s coplanar ratio principle - the relaxed coplanar ratio principle, according to which surfaces in space that are parallel and facing the same direction can be grouped and compared for lightness by the visual system, as they are often equally illuminated.

In an experiment designed to pit these two hypotheses against each other, Gilchrist and Radonjić showed that the results fit better with the relaxed coplanar ratio principle predictions than predictions based on the ELM. In contrast, when Maloney, Doerschner and Brainard (2007) pit the two hypotheses against each other, they find that neither of the two hypotheses can account well for the data they obtained, suggesting that a definite answer about the mechanism used by the visual system to estimate surface lightness in a three-dimensional scene requires further research.

The experiments I conducted are not designed to test between these two hypotheses. Instead they contribute to understanding the conditions under which target lightness changes with a change in spatial relations. The data obtained across experiments need to be accounted for by any comprehensive theoretical account of lightness computation in complex three-dimensional scenes. For example, one challenge for the ELM type of model would be to account for the effect of articulation on lightness found in Experiment 2.

Dimensionality of perceived illumination

Both the coplanar ratio principle and the anchoring theory implicitly treat perceived illumination as a two-dimensional concept: it is based on luminance relations within a plane and it affects target lightness when the target is perceived to belong within that plane. Contrary to this view, Ikeda et al. (1998) propose the idea that the perception of illumination is three-dimensional i.e. related to a certain volume of space, rather than a plane or surface of an object. According to Ikeda et al. (1998), the visual system constructs *a Recognized Visual Space of Illumination* (RVSI), a "cortical representation of illuminant for a space" (Churhansaksiri et al. 2004, p. 255) based on the initial visual information available in the image. The RVSI has properties such as size, equivalent to intensity, and color, equivalent to chromaticity and once it is formed it enables the visual system to judge the properties of objects contained within it.

The idea of RVSI is very close to the Helmholtzian idea that the visual system estimates the illumination and takes it into account when judging the color and lightness of an object, as well as the neo-Helmholtzian Equivalent Lightning Model proposed by Boyaci et al. (2006).

Also, the idea of RVSI is consistent with the findings of both the Gilchrist perpendicular and parallel planes experiments, with the difference that surface lightness is not determined in relation to the plane, but in relation to the space (Ikeda et al.,1998, 2006). Interestingly, Ikeda et al. can also account for the difference in results between experiments done using simulated displays and those using real paper and illuminant displays (e.g. Schirillo et al., 1990; Howe, 2006 vs. Gilchrist, 1977, 1980) in terms of RVSI, as in two-dimensional computer displays determining the relevant space and consequently the lightness of a simulated object becomes increasingly difficult (Ikeda et al., 2006).

Empirically, it is difficult to tease apart these two hypotheses about the dimensionality of perceived illumination, given that most of the time both would give the same prediction about target lightness. Theoretically, the idea of the RVSI is economical because it allows the visual system to maintain the same perceived object color/lightness as long as the surface is in the same space of illumination, rather than continuously updating surface lightness as the surface moves across different planes in the image (Ikeda et al., 1998).

Ikeda and his collaborators do not propose an exact mechanism by which the visual system actually construes the visual space of illumination or how does it delineate RVSI boundaries. In that respect, it is important to note that the concept of RVSI and the anchoring theory are not mutually exclusive. Even if the visual system determines surface lightness based on an estimate of perceived illumination in the space, this idea would be consistent with the anchoring theory if the frameworks are defined as three-dimensional, while applying the mechanism of computation proposed by the anchoring theory.

The experiments I have conducted were not in any way aimed to test whether the perception of illumination is two-dimensional or three-dimensional. The majority of experimental results fit both hypotheses. According to the RVSI hypothesis, as the target moves from one plane to another, it moves from one RVSI to another and its lightness changes accordingly. The RVSI hypothesis can also account for the effect of articulation because it proposes that articulation of spaces provides more initial visual information, used by the visual system to form an accurate estimate of the RVSI (Ikeda et al., 1998). This could account for the difference in the depth effect when the planes of the display are articulated compared when they are homogenous (Experiment 1 vs. 2, Experiment 6 vs. 6A). However, the RVSI hypothesis cannot account for the differential effect of articulation in the binocular and in the monocular conditions of Experiment 2. Also, it is not clear how would it explain the results of Experiment 5 when target lightness changes as it moves from the position in which it is embedded in its retinal background (monocular condition) or floating in front of it (binocular condition) nor why surrounding the target with a high-luminance border and not a low-luminance border affects the target lightness (Experiment 5A) as it is not clear how the RVSI changes across conditions in these cases.

Appendix I: Instructions verbatim

Detailed and lengthy instructions were introduced after the results of the pilot study showed that the obtained difference between the target matches was very small, unlike Gilchrist (1977). It is possible that such results were obtained due to unclear instructions given to the observers “to pick a chip from the scale that is the same shade of gray as the target”.

When asked to match the shade of gray of the target, the observers may have actually matched the appearance of the target under the given illumination conditions, thus making a brightness and not a lightness match. Numerous studies have shown that the instructions in lightness/brightness judgment tasks can have significant effects on observers matches and that understanding the difference between the two notions is an essential condition for validity of matches in this type of matching task (Arend & Goldstein, 1987; Schirillo, Reeves & Arend, 1990; Ripamonti et al., 2004). The following introduction was given to the observers to ensure that they understood that their task in the experiment was to make lightness, not brightness matches:

“In this lab, we are interested in lightness perception. That means: how do we perceive what shade of gray is the surface of an object; how do we know that a certain surface is white, black or gray? This might sound like a trivial question but actually it can be quite complicated. I’ll try to explain a little more about it, so you will understand better what your task will be in the experiment.”

“Imagine you are somewhere outside on a sunny summer day wearing a white T-shirt. Your T-shirt will look very bright. It will get a lot of light and it will emit a lot of light. Then, imagine you move to a dark room. Now, your T-shirt will look much darker.

But if I ask you what is the color of your T-shirt now, you will tell me it's white, because things don't change color as they move from one illumination to another. They may appear brighter or darker, but their actual color remains the same. In this study, I am interested in that *stable* property of the surface that does not change from one illumination to the other."

"In this experiment, I'll be showing you different things, which I call targets. I'll be asking you "what color is this surface, what color is that surface" and what I'll mean by that is "what is the *actual* color of that surface, and not how does that surface appear in that particular moment under that particular illumination. Now, I will show you an example. Take a look at this display".

Observer is then shown a 55 x 22 cm display consisting of 5 vertical rectangles (11 x 22 cm each) of different shades of gray (ranging from 5.5% to 36.2% reflectance), placed one next to another. The display was illuminated by a 100W incandescent bulb, positioned 95 cm above the display. A shadow-caster was placed 26 cm above the display so that it created a shadow on the half of the display, covering the upper half of all five rectangles, so that the display appeared to contain 10 different shades. The experimenter pointed to the lower, brightly illuminated portions, of the two most left patches of different shade of gray and said:

"If I asked you to tell me what is the color of this patch [pointing to the far left one, reflectance 5.5%] and what is the color of this patch [pointing to the patch next to it, reflectance 12%] you would tell me two different colors, since these two patches are different in actual color. But if I asked you what is the color of this patch [pointing again to the lower part of the far left patch] and what is the color of this patch [pointing to the upper part of the same patch in the shadow] you would tell me the same color. The upper patch appears darker than the lower, but that difference is only due to the illumination. However, I am not interested in differences in appearance due to the illumination. I am only interested in the actual color – and the actual color of these two patches is the same.“

Following this example, the observer was introduced to the Munsell chart and the matching task was explained.

“You will be using this chart [pointing to the Munsell chart], which consists of chips of different shades of gray, from white to black and is under this special illumination. The targets are not going to be on the chart, under that illumination, but somewhere in the display [pointing to the inside of the vision tunnel]. When I ask you what color a target is, I am actually asking you: if we took the target out of the display, and placed it on the chart, so it was under the same illumination as the chart, what chip from the chart would it match then? In other words, what chip from the chart is the same actual color as the target? What chip from the chart is cut from the same piece of paper as the target?”

Appendix II:

Results of three[38] separate 2 x 2 repeated measure ANOVAs, with target (upper - lower) as a within-subject and a viewing condition (monocular - binocular) as a between-subject factor, conducted for each luminance range condition (Experiment 6).

In the 110:1 condition, the ANOVA revealed a marginally significant main effect of target $F(1, 28) = 3.29$, $p = 0.08$ and a significant effect of viewing condition, $F(1, 28) = 5.85$, $p < 0.05$. Overall, the targets were perceived as darker in the monocular (M = 1.03, SE = 0.05) than in the binocular condition (M = 1.2, SE = 0.05), and the upper target was perceived as darker (M = 1.04, SE = 0.05) than the lower target (M = 1.18, SE = 0.06). The ANOVA also revealed a Target x Condition interaction, $F(1, 28) = 74.32$, $p < 0.001$ (see lightness judgment for 110:1 range in the monocular and in the binocular condition in Figure 22 for comparison).

Paired t-tests revealed that the two equiluminant targets differed in lightness within both the binocular condition ($t(14) = 4.75$, $p < 0.001$) and the monocular condition ($t(14) = 7.50$, $p = 0.001$). Independent t-tests revealed that the lower target appeared significantly lighter in the binocular condition than in the monocular condition, $t(28) = 7.55$, $p < 0.001$, while the upper target appeared significantly darker in the binocular condition than in the monocular condition, $t(28) = 4.99$, $p < 0.001$.

In the 53:1 condition, the ANOVA revealed a significant main effect of target $F(1, 28) = 4.44$, $p < 0.05$ and a significant effect of viewing condition, $F(1, 28) = 12.96$, $p < 0.001$. Overall, the targets were perceived as darker in the monocular (M = 0.90, SE =

[38] For results for 900:1 range see result section of Experiment 1.

0.04) than in the binocular condition (*M* = 1.11, *SE* = 0.04). Overall, the upper target was perceived as darker (*M* = 0.94, *SE* = 0.04) than the lower target (*M* = 1.07, *SE* = 0.05). The ANOVA also revealed a Target x Condition interaction, $F(1, 28) = 99.79$, $p < 0.001$ (see lightness judgment for 53:1 range in the monocular and in the binocular condition in Figure 22 for comparison).

Paired *t*-tests revealed that the two equiluminant targets differed in lightness within both the binocular condition ($t(14) = 7.60$, $p < 0.001$) and the monocular condition ($t(14) = 6.50$, $p = 0.001$). Independent *t*-tests revealed that the lower target appeared significantly lighter in the binocular condition than in the monocular condition, $t(28) = 8.73$, $p < 0.001$, while the upper target appeared significantly darker in the binocular condition than in the monocular condition, $t(28) = 5.79$, $p < 0.001$.

In the 30:1 condition, the ANOVA revealed a significant main effect of target $F(1, 28) = 6.77$, $p < 0.05$ and a significant effect of viewing condition, $F(1, 28) = 9.61$, $p < 0.004$. Overall, the targets were perceived as darker in the monocular (*M* = 0.81, *SE* = 0.06) than in the binocular condition (*M* = 1.05, *SE* = 0.06). Overall, the upper target was perceived as darker (*M* = 0.84, *SE* = 0.04) than the lower target (*M* = 1.05, *SE* = 0.07). The ANOVA also revealed a Target x Condition interaction, $F(1, 28) = 36.77$, $p < 0.001$ (see lightness judgment for 30:1 range in the monocular and in the binocular condition in Figure 22 for comparison).

Paired *t*-tests revealed that the two equiluminant targets differed in lightness within both the binocular condition ($t(14) = 4.54$, $p < 0.001$) and the monocular condition ($t(14) = 5.85$, $p = 0.001$). Independent *t*-tests revealed that the lower target appeared significantly lighter in the binocular condition than in the monocular condition, $t(28) =$

5.33, $p < 0.001$, while the upper target appeared significantly darker in the binocular condition than in the monocular condition, $t(28) = 2.52$, $p < 0.05$.

In all the luminance range conditions, paired tests exploring Target x Condition interaction showed that the target that appeared coplanar with the lighted side of the display was perceived as significantly darker than the target that appeared coplanar with the shadowed side of the display in both binocular and monocular conditions.

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