

Adjacency and surroundedness in the depth effect on lightness

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Using two perpendicular planes, one brightly and one dimly illuminated, A. L. Gilchrist (1977) showed that target lightness can change nearly from black to white by changing its perceived spatial position, with no change in the retinal image, if the target has an adjacent coplanar neighbor in each position. Earlier L. Kardos (1934) found a modest depth effect for a target that was not adjacent to its coplanar neighbor but surrounded by it. Using Kardos' experimental arrangement, but articulated planes and a between-subjects design, we obtained a large depth effect on lightness without adjacency. We then explored the role of adjacency and surroundedness using Gilchrist's perpendicular planes arrangement. We replicated the large depth effect when the target was adjacent to its coplanar neighbor. However, most of this depth effect was lost when adjacency was eliminated, by moving each target within its plane away from its coplanar neighbor. When we surrounded each target by extending its non-adjacent coplanar background, half the effect provided by adjacency was restored, but only in the brightly illuminated, not the dimly illuminated plane. Our findings support the view that, to compute surface lightness, the visual system groups surfaces in the image that seem to be equally illuminated.

Keywords: lightness perception, depth perception, coplanarity, adjacency, surroundedness

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Introduction

Lightness, or the perceived shade of gray of a surface, is the perceptual property of a surface corresponding to the physical property of reflectance, that is, the proportion of incident light a surface reflects. Lightness perception is problematic because the intensity of light that travels from the surface to the eye, called luminance, is a product of both surface reflectance and incident illumination. The exact mechanism by which the visual system computes lightness from luminance is still not well understood.

In the late 19th century, Mach (1886/1959) described his now well-known bent card illusion, in which a change in perceived depth leads to a change in lightness. However, despite this convincing demonstration, for many decades during the mid-20th century, it was widely believed that depth perception plays no important role in lightness perception. Several empirical tests, some of which, like Beck (1965) used the Mach bent card illusion as a stimulus, reported little (Beck, 1965; Coren, 1969; Flock & Freedberg, 1970; Gogel & Mershon, 1969; Hochberg & Beck, 1954) or no (Epstein, 1961; Gibbs & Lawson, 1974; Julesz, 1971) effect of depth on lightness.

The majority of the published reports viewed lightness as the product of luminance ratios between retinally adjacent regions (Wallach, 1948), possibly mediated by the mechanism of lateral inhibition (Cornsweet, 1970; Diamond, 1953; Fry & Alpern, 1953; Heinemann, 1955; Jameson & Hurvich, 1964; Leibowitz, Myers, & Chinetti, 1955).

In 1977, Gilchrist reported strong effects of depth perception on lightness perception (see also Gilchrist, 1980). In that work, a target surface shifted in appearance from nearly white to nearly black, or vice versa, merely as a function of its perceived spatial position, with no significant change in the pattern of retinal stimulation. Based on these findings, Gilchrist proposed a coplanar ratio principle, according to which, when the surface has an adjacent coplanar neighbor and the luminance range in the image is much larger than 30:1, lightness depends on the luminance ratio of the target surface and its adjacent neighbor that is perceived to lie in the same plane (Gilchrist, 1980). Although Gilchrist asserted that adjacency was a necessary condition for lightness computation to be based on coplanar, rather than retinal ratios, he offered no empirical evidence. However, relevant evidence about the role of adjacency comes from a much earlier Gestalt study.

More than four decades before the Gilchrist work, the Gestalt psychologists had emphasized the influence of depth perception on lightness. Koffka (1935) noted that coplanarity is an important grouping principle for lightness, and both Katona (1929, 1935) and Wolff (1933) reported depth effects in lightness. However, the work that most clearly anticipated the later findings of Gilchrist was reported by Kardos in his important, but neglected, 1934 book *Ding und Schatten* (Object and Shadow). One of his many experimental arrangements featured a large, brightly illuminated rectangular white panel mounted on a table and positioned in the observer's frontal plane. The panel contained a large circular aperture through which the observer could see a black dimly illuminated parallel plane. The position of the target disk centered within the aperture was varied across conditions so that it was seen either in the near plane, coplanar to the brightly lit white panel, or in the far plane, coplanar to the dimly lit black background, while its retinal image was kept constant (see Figure 1). Kardos reported that the disk appeared lighter in the far plane than in the near plane (by about 1.1 steps when converted into Munsell units).

Based on the previous work on the effect of depth on lightness (Beck, 1965; Coren, 1969; Epstein, 1961; Flock & Freedberg, 1970; Gibbs & Lawson, 1974; Gogel & Mershon, 1969; Hochberg & Beck, 1954, Julesz, 1971), as well as his own experiments, Gilchrist (1980) concluded that when a single surface is isolated in a plane, without a coplanar adjacent neighbor, target lightness will by default be determined by retinal ratios (Gilchrist, 1980). This hypothesis is consistent with the findings of Kardos (1934) who reported that when the bright surround is removed, the front disk, now isolated in its plane, appears lighter.

However, contrary to Gilchrist's claim that adjacency is necessary for the lightness computation based on coplanar ratios, the results reported by Kardos suggest that, when the target surface is not isolated in its plane, other coplanar surfaces can serve as a standard for lightness computation even if they are not adjacent to the target.

Yet, the implications of the Kardos results for Gilchrist's adjacency claim are not entirely clear. The depth effect Kardos obtained without target/background adjacency was much weaker (only about 1.1 Munsell units) than that reported by Gilchrist (about 4.5 Munsell units) and this difference in size of the effect may have been the result of the lack of adjacency.

In addition, the Kardos study had several methodological shortcomings that prevent accurate estimation of the size of the depth effect he obtained and its validity: (1) the target disk luminance was not carefully measured and reported across experimental conditions, (2) the estimate of the depth effect was based on a small number of subjects, (3) the within-subjects experimental design used by Kardos is known to substantially reduce the depth effect when compared to a between-subjects design (Coren, 1969; Gilchrist, 1980; Gogel & Mershon, 1969),

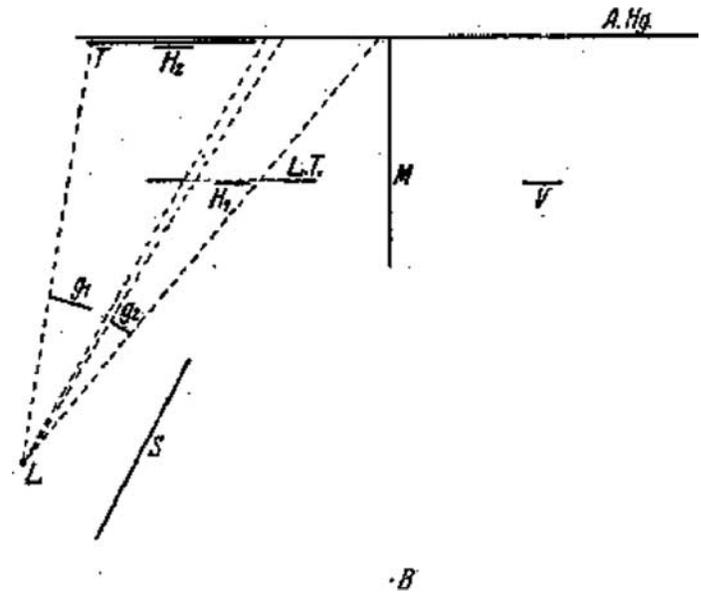


Figure 1. Schema of the original experimental arrangement of Kardos (1934). A vertical screen (M) divided the laboratory into a stimulus area (on the left) and a matching area (on the right). In the stimulus area, two light gray disks (44.6% reflectance), identical in luminance and retinal size, served as targets in the experiment. The front target disk (H_1) was coplanar to the white panel (L.T.) and suspended in the middle of a circular aperture cut in the middle of the panel. The back target disk (H_2) was lying in the plane of the black background (T), which, in this condition, was equal in reflectance to the general background (A.Hg.). While the white panel was illuminated by a 60-W lamp (L), the black background and the area of the hole within which the front disk was suspended were in the shadow produced by shadow casters (g_1, g_2). The penumbra of the cast shadow covering the front disk fell within the gap between the disk and the white panel and was not visible to the observer. The lamp and the shadow casters were occluded from the observer's view by another screen (S). The observer viewed the scene from position B and matched lightness of the target disks by adjusting the matching disk (V), placed in the dimly illuminated matching area. All disks (H_1, H_2 , and V) were color mixers with motors, whose lightness could be adjusted by varying the size of the white sector (in degrees of angle).

and (4) Kardos reported only means, with no measure of variability, and thus no way to assess the statistical reliability of the effect.

Experiment 1: Kardos replicated

To clarify whether large effects on lightness can be obtained in the absence of adjacency, we replicated the original Kardos experiment.

In the preliminary pilot study, we used an experimental arrangement identical to the original study that featured homogenous planes and we obtained a depth effect of 1.35 Munsell units, similar to what Kardos had reported.

Knowing from previous work that articulation, that is the complexity of the stimulus defined by the number of surfaces within a field or framework, can significantly affect the depth effect (e.g., compare Schirillo, Reeves, & Arend, 1990 with Schirillo & Arend, 1995), we added a number of surfaces to the shadowed background plane in order to maximize the depth effect on lightness.

Methods

Experimental setup: A large rectangular white panel 101 cm wide and 76 cm high was mounted in a vertical position, 88 cm in front of the back wall, facing the observer, with its bottom edge resting on a laboratory bench 94 cm above the floor. A large circular hole, 56 cm in diameter, was cut out of its center. A large black panel, partially visible through the hole, was mounted against the back wall with eight pieces of rectangular white paper pasted haphazardly across it.

Distal stimulus: Two cardboard disks covered with white Color-Aid paper served alternately as targets. The smaller disk, 20 cm in diameter, was suspended in the center of the hole, coplanar with the white panel and separated from it by 18-cm gap. It was supported by an aluminum rod that extended from the back wall but was hidden from the observer by the disk itself. The larger disk, 28 cm in diameter, was mounted on the black back panel, centered within the hole, from the observer's viewpoint.

Illumination conditions: The sole illumination was provided by an obliquely positioned 100-W incandescent bulb, mounted at a location approximately 175 cm in front of the white panel and 145 cm to the left of the center of the hole. While the entire white panel was directly illuminated by this light source, the back black panel received no direct light, being shaded by both the white panel and an additional panel that covered the left side of the space between the white and black panels. An oval-shaped shadow caster was mounted between the light source and the white panel so as to cast a shadow within the hole that could completely cover the smaller disk, with no penumbra visible (see Figure 2).

Observer position: The observer sat in a chair facing the display, using a chin rest. The observer's eye was at the same height (132 cm) above the floor as the two target disks, and 220 cm from the white panel.

Proximal stimulus: At this viewing distance, both target disks subtended the same visual angle of 5.2° . The luminance of the front disk was 0.41 cd/m^2 and the luminance of the back disk was 0.40 cd/m^2 . Due to the oblique position of the light source, the white panel had a luminance gradient, resulting in luminance measurements

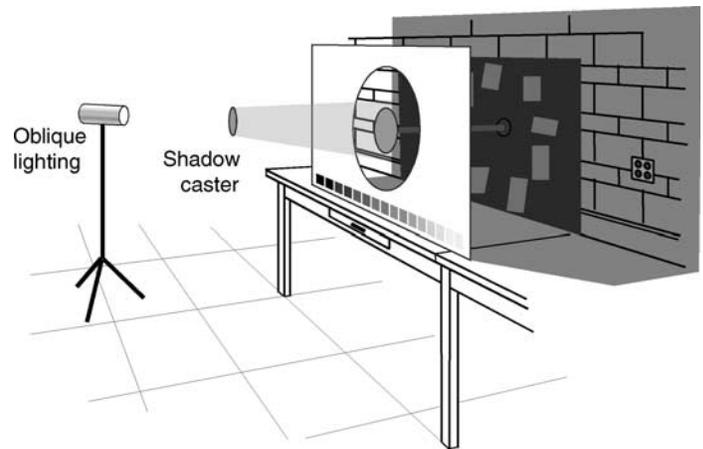


Figure 2. Laboratory arrangements in the Kardos replication, with the target disk in the front position.

of 44.2 cd/m^2 to the left of the hole, and 26.72 cd/m^2 to the right of the hole. Due to photometer unreliability at low luminance levels, the luminance of the black background could not be accurately measured. Based on the fact that the far disk was made of white paper and the background was made of black paper, we estimate that the background luminance was between 25 and 30 times darker than the back disk ($0.13\text{--}0.2 \text{ cd/m}^2$).

Matching chart: Matching was done using a Munsell chart mounted on the white panel below the hole. The chart consisted of 16 chips mounted on a white background and arranged in ascending reflectance order from Munsell 2.0 (3% reflectance) to Munsell 9.5 (90% reflectance) in 0.5-step increments.

Observers: A total of 20 undergraduates from Rutgers University volunteered to serve as observers in the experiment. Each observer provided two Munsell matches, one for the front disk and one for the back disk, with 10 observers matching the disks in one order (front disk first, back disk second) and 10 in the reverse order.

Instructions: The observers were initially acquainted with the scene without the disks and were asked to turn around while each disk was being put into place. The spatial position of each disk was pointed out to the observer, but the illumination arrangement was not discussed. For the matching task, we used a clearly distally focused lightness instruction, stressing to observers that the disks were cut out of some piece of paper, and that they were to call out the number of the corresponding piece of paper from the Munsell chart as best they could.

Results and discussion

In all the experiments we report, Munsell matches have been converted into log reflectance for the purpose of data analysis, but Munsell values are provided for readers more

familiar with that scale (ranging from typical black, Munsell 2.0, to a typical white, Munsell 9.5). The mean lightness matches for the front and back target disks are plotted in Figure 3. We conducted a two-way repeated measures analysis of variance (ANOVA) with disk position (front vs. back) as a within-subjects factor and presentation order (front first vs. back first) as a between-subjects factor.

Consistent with the report of Kardos, we found that the front disk appeared significantly darker than the back disk (main effect of disk position, $F(1,18) = 137.98$; $p < 0.001$). In the crucial between-subjects comparison involving only the first presentation seen by each group of observers, the front disk appeared close to black (Munsell 2.75 or 0.74 log reflectance) while the back disk appeared light gray (Munsell 7.15 or 1.64 log reflectance), yielding a lightness shift of 4.4 Munsell steps (0.91 log reflectance) caused solely by the shift in perceived depth, with no significant change in retinal pattern, $t(18) = -12.31$, $p < 0.001$. We will refer to this shift as the depth effect.

Our between-subjects depth effect of 4.4 Munsell units is substantially larger than the 1.1 Munsell depth effect of Kardos. There are two main differences between our

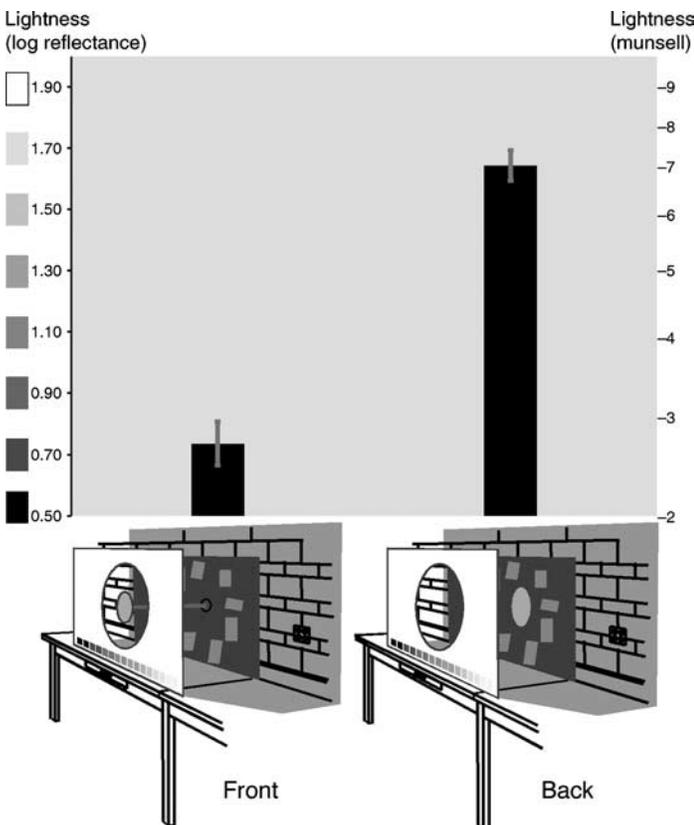


Figure 3. Lightness of the disk in the front and back positions in Experiment 1. Each data point represents the mean matched lightness over observers expressed in log reflectance with error bars indicating ± 1 between-subjects SEM. A perspective view that illustrates the perceived spatial arrangement (not the observer's retinal image) for the disk in the front and for the disk in the back is shown on the X-axis.

experiment and the Kardos experiment that can account for this difference in results: (1) order effect and (2) articulation.

Combining all front disk matches, regardless of order, and all back disk matches yields a within-subjects depth effect of 3.6 Munsell units (0.74 log reflectance; front target: Munsell 3.2, $M = 0.86$ log reflectance, $SE = 0.05$; back target: Munsell 6.8, $M = 1.60$ log reflectance, $SE = 0.04$; also see main effect of disk position).

These results illustrate the problem of order effects in studies of depth and lightness. It appears that the lightness matches made in the second of two depth arrangements seen by a given subject are strongly constrained by those of the first arrangement seen.

Further, unlike in the experiment of Kardos, in our study the dimly illuminated black background was articulated, containing a number of surfaces besides the target disk. This would be expected to result in an increase in the depth effect.

We can estimate, at least roughly, the relative contributions of the order effect and articulation, the two main points of difference between our study and that of Kardos.

Comparing our between-subjects effect of 4.4 with our within-subjects effect of 3.6, while keeping the (high) articulation constant, gives an order effect of 0.8 Munsell units. Comparing our 4.4 depth effect with our low articulation pilot effect of 1.3, while keeping the between-subjects design constant, gives an articulation effect of 3.1 units. In addition, comparing our effect of 3.6 with the effect of 1.35 from our pilot study (or 1.1 of Kardos), with the within-subjects design held constant, gives an articulation effect of 2.25–2.5 Munsell units. While flawed in certain ways, these comparisons suggest that, of the two main modifications we made to the Kardos method, adding articulation was the most effective.

The role of adjacency in the depth effect

Our finding establishes that it is possible to get large depth effects without target/background adjacency, contrary to Gilchrist's earlier assertion. However, the role of adjacency between the target and its coplanar neighbor still remains unclear.

Note that in his experimental arrangement Gilchrist used adjacency but unarticulated planes and produced the 4.5 unit depth effect. Both the original arrangement of Kardos and our pilot study also featured unarticulated planes, but no adjacency between coplanar surfaces, producing a 1.1–1.35 unit depth effect. This comparison seems to suggest that adjacency is important.

The point is further supported by an additional pilot condition we ran using the Kardos arrangement, in which we increased the size of the gap between the target disk and the white panel from 18 cm to 23 cm by reducing the size of the disk from 20 cm to 10 cm in diameter (2.6° of visual angle). A separate group of 8 observers judged the small front disk as slightly lighter than the large front disk in the main experiment (Munsell 3.2). This finding

indicates that the depth effect is inversely related to the size of the gap between the target and its coplanar surround and is consistent with the earlier work on the separation between inducing and test surfaces (Fry & Alpern, 1953; Leibowitz, Mote, & Thurlow, 1953; Newson, 1958). Note, however, that in our pilot study, the gap size was confounded with disk size.

To clarify these issues, we directly tested whether adjacency is necessary for the large depth effects on lightness using Gilchrist's perpendicular planes arrangement, in which large depth effects (with target and coplanar neighbor being adjacent) have already been well established.

Experiment 2: Depth effect with adjacency (a baseline measure)

We first replicated the Gilchrist (1977, 1980) perpendicular planes experiment to confirm that our laboratory conditions were not different in any important way and to establish the size of the depth effect on lightness when the target has a neighboring surface that is both coplanar and adjacent.

We 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, producing a large luminance range. 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, and 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: each target appeared coplanar with the side of the display from which it extended. 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, across the two viewing conditions (monocular vs. binocular) each target was 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 predicts that target lightness will change substantially as a function of the luminance ratio between the target and its perceived adjacent coplanar neighbor (Gilchrist, 1980).

Methods

Apparatus: The experimental setup was arranged in a vision tunnel (117 cm long \times 60 cm wide and high), 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 stimulus chamber was painted matte black, except for the floor and the right sidewall that were covered with gray paper (Color-aid 4.5, reflectance 24.6%) and the back wall that was covered with matte white paper (reflectance 90%; Figure 4).

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 chamber floor). The two visible sides of the "cube" met at a vertical right angle pointing toward the observer. Each side of the cube was 11 cm square and constructed from Color-aid paper, the left side black (reflectance 3.1%) and the right side white (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 (Figure 5).

Two nearly square paper targets, 4.5 cm wide and approximately 4 cm high, extended from the dihedral corner itself. Each Color-aid paper target was bonded to a thin metal panel for rigidity. The lower, white target (reflectance 90%) extended from the black side and was seen against the white side of the display. The upper, black target (reflectance 3.1%) extended from the white side and was seen against the black side of the display. Although each target physically lay in one plane of the dihedral corner, its linear perspective was made consistent with that of the other plane by cutting the target in a slightly trapezoidal shape. Thus, when viewed monocularly through the pinhole, the target appeared to lie in the orthogonal plane, the one it was seen against.

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 dim illumination.

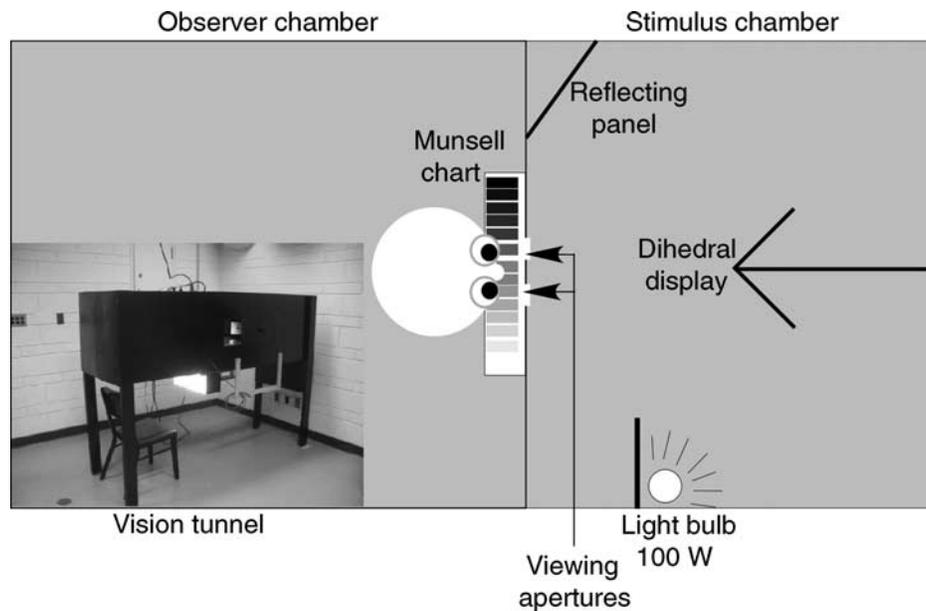


Figure 4. Plan view of the experimental apparatus (drawn to scale). A photograph of the vision tunnel in the laboratory is shown in the bottom left corner.

The illumination ratio between the two sides of the display, approximately 30:1, was equal and opposite to the reflectance ratio between the white and black targets, equating their luminances. This was achieved by mounting a reflecting panel, consisting of a piece of white paper on a black foam-board panel, in the near left corner of the chamber 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 onto the white target could be adjusted with 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° and 4.8° of visual angle horizontally.

Photometric measurements were taken using a Konica Minolta LS-100 luminance meter. The luminance of both targets was 17.6 cd/m^2 . The luminances of the shadowed black side and the lighted white side of the display were 0.59 cd/m^2 and 528 cd/m^2 , for a luminance range of about 900:1. The luminance of the background wall varied from 525 cd/m^2 on the right side to 242 cd/m^2 on the left side. As in [Experiment 1](#), due to photometer unreliability at low luminance levels, the luminance of the shadowed black side of the display could not be accurately measured. Its reported luminance (in [Experiments 2–4](#)) is an estimate obtained by measuring the luminance of the white surface at the same position and dividing it by the ratio of reflectance of the white paper to the reflectance of the black paper.

Matching chart: Matching was done using a Munsell chart, similar to that used in [Experiment 1](#), consisting of 16 chips, $1 \text{ cm} \times 3 \text{ cm}$ each, mounted on the white

background. The chart was housed in a metal chamber mounted 48 cm directly below the viewing apertures and separately illuminated by a 15-W fluorescent tube. The luminance of the white chip was 360 cd/m^2 .

Instructions: At the beginning of the experimental session, each observer was given lengthy instructions, which included an explanation of the concepts of lightness and brightness with concrete examples, introduction to the Munsell chart, and explanation of their task in the experiment. These instructions, accompanied by a description of

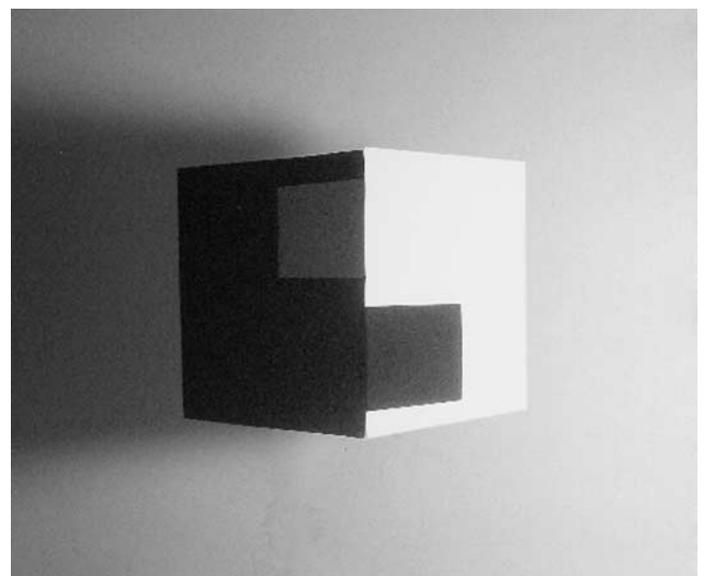


Figure 5. A photograph of the display from the observer's viewpoint.

our demonstrations, are available at <http://psychology.rutgers.edu/~alan/dlinstructions.html>.

The observer was then asked to take a seat in the observer chamber and look into the tunnel through the aperture(s). In the binocular condition, the observer was asked to look through the 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 the corner of a cube, with one side darker and another side lighter and then asked questions to establish the perceived spatial position of the targets. The observer was then 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. The surprise of observers participating in the monocular condition after the actual position and reflectance of the targets was revealed to them served as a further confirmation that the experimental manipulation of perceived position of the targets was successful.

Observers: Separate groups, each consisting of 20 observers, matched the target lightness in each condition, half the observers judging the lower target first and half the observers judging the upper target first.

Criteria for exclusion: Three criteria for the exclusion of observer responses from the data analysis were applied throughout Experiments 2–4. Observer matches were excluded when (1) the observer failed to perceive the intended spatial position of the targets, (2) during debriefing session we established 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.”), and (3) the observer matches fell more than 3 standard deviations above or below the mean of the whole group in a given condition (excluding the match of the potential outlier/s). 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 the binocular condition of the experiment: three for making brightness instead of lightness matches and one for being an outlier.

Results and discussion

The mean lightness matches for each target in the monocular and binocular conditions are shown in Figure 6.

Note that, unless specified otherwise, in the analysis and discussion of the results, we will use the term coplanarity

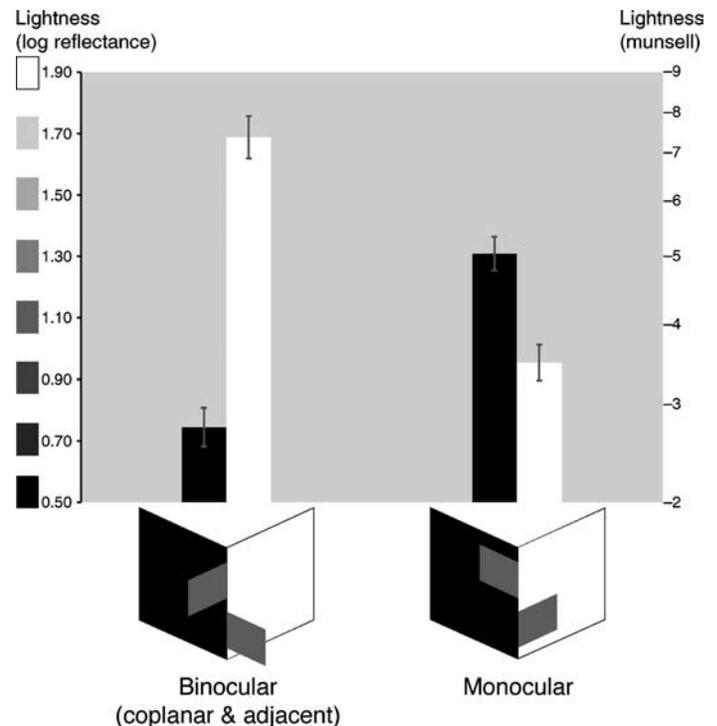


Figure 6. Target lightness in Experiment 2. The figure follows the same conventions of data presentation as Figure 3. A perspective view that illustrates the perceived spatial arrangement (not the observer’s retinal image) in the binocular and monocular conditions is plotted on the X-axis. Lightness of the upper, lighted black target shown in black. Lightness of the lower, shadowed white target shown in white.

to mean *perceived* coplanarity. Thus, instead of saying “target that appears coplanar to one side of the display” we will simply say: “target coplanar to one side of the display.”

The basic depth effect obtained by Gilchrist (1977, 1980) was replicated. The lightness of each target changed substantially as a function of the plane to which it was perceived to belong, across conditions (Target \times Condition interaction, $F(1, 38) = 81.11, p < 0.001$; see Figure 6). The lower target appeared light gray (Munsell 7.6 or 1.69 log reflectance) when coplanar with the shadowed side of the display in the binocular condition, but dark gray (Munsell 3.6 or 0.95 log reflectance) when coplanar with the lighted side of the display in the monocular condition, $t(38) = 6.78, p < 0.001$. The upper target appeared nearly black (Munsell 2.85 or 0.74 log reflectance), when coplanar with the lighted side of the display in the binocular condition, but middle gray (Munsell 5.2 or 1.31 log reflectance) when coplanar with the shadowed side of the display in the monocular condition, $t(38) = 8.16, p < 0.001$.

Consistent with the coplanarity principle, the target coplanar with the lighted side of the display (upper in the binocular; lower in the monocular condition) appeared darker than the target coplanar with the shadowed side

(lower in binocular; upper in monocular condition) in both binocular, $t(19) = 8.12$, $p < 0.001$, and monocular conditions, $t(19) = 4.16$, $p = 0.001$.

Within each condition, we measured the depth effect, equal to the difference in perceived lightness of the two equiluminant targets, which appear to lie in different planes, having different coplanar adjacent luminance. In the binocular condition, the depth effect yielded 4.8 Munsell units (0.94 log reflectance) and was significantly larger than that in the monocular condition (1.6 Munsell units or 0.35 log reflectance; $t(38) = 4.08$, $p < 0.001$), possibly because the two planes were not as well segregated perceptually in the absence of stereo information.

Experiment 3: Direct test of adjacency

To assess the importance of adjacency within a plane, the perpendicular planes setup from [Experiment 2](#) was modified by moving each target within its plane, away from its coplanar side of the display, so it appeared to float in space, with no adjacent 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; equivalent to the lower target in [Experiment 2](#)) appeared coplanar with the shadowed side of the display and the equiluminant brightly illuminated black target (left target, equivalent to the upper target in [Experiment 2](#)) appeared coplanar with the lighted side of the display. When viewed monocularly (embedded condition), each target appeared to lie embedded in the side of the display it was seen against: the right one coplanar and surrounded by the lighted side and the left one coplanar to and surrounded by the shadowed side of the display (the

icons in [Figure 8](#) indicate the perceived spatial arrangement in the stimulus in each condition).

If adjacency within a plane is not a necessary condition for coplanar lightness computation and mere coplanarity is sufficient, then the binocular results for this experiment will be the same as the binocular results of [Experiment 2](#). If adjacency within a plane is a necessary condition, then the depth effect we obtained in the binocular condition of [Experiment 2](#) will either be weakened or completely eliminated. In the latter case, target lightness will be determined solely by retinal ratios, and as these do not change across conditions, perceived lightness will not change for either target.

Methods

[Experiment 3](#) was identical to [Experiment 2](#) in all respects except that each target was moved laterally within the same plane away from its neighboring side of the display so that it appeared to float in midair coplanar with that side of the display but separated from it by a 2-cm gap. This new target position required a corresponding slight change in both target shape and the illumination conditions. Each target was supported by a 7-cm-long rigid wire attached to the center of a background square but occluded from view by the target itself, as seen in [Figure 7](#).

To avoid casting a visible shadow of the wire supporting the right target, the incandescent bulb used in [Experiment 2](#) was replaced with a 15-W fluorescent tube mounted in a vertical position on the right wall of the stimulus chamber. This rendered the shadow invisible by smearing it vertically across the white background square.

Proximal stimulus: Each target (4.5×4 cm) 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 2](#), with the following values in cd/m^2 :

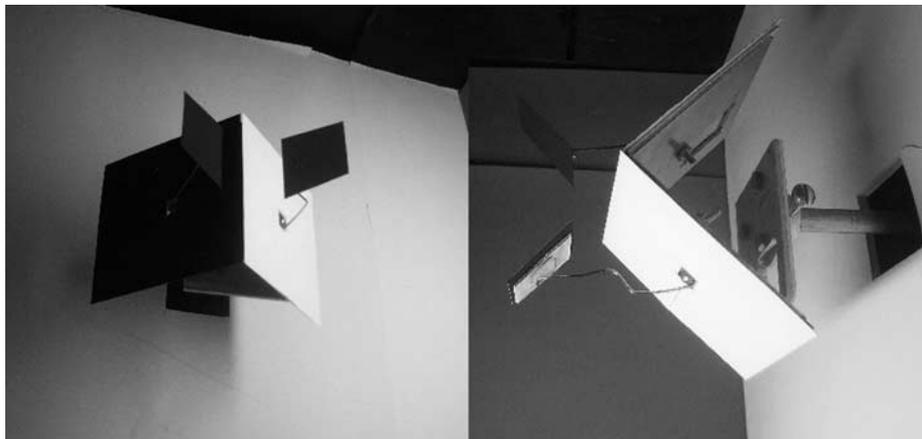


Figure 7. Stimulus setup in [Experiment 3](#) from two viewpoints, both different from the observer's view.

targets, 12; left background 0.4; right background, 367. The luminance of the background wall varied from 138 just below the display to 305 on the right side of the display.

Observers: A separate group of 15 observers viewed the display in each of the two conditions. One observer was excluded (and replaced) from the coplanar only condition as an outlier.

Results and discussion

The mean lightness matches for each target in the coplanar only and embedded conditions are plotted in Figure 8.

The disruption of adjacency of the target and its coplanar surface within each plane eliminated most of the depth effect we had obtained in Experiment 2. In the coplanar only condition, the significant difference obtained between the targets, $t(14) = 2.53$, $p < 0.05$, was opposite to the depth effect obtained in Experiment 2. That is the left target, coplanar to the lighted side of the display, appeared lighter, not darker, than the right target, coplanar to the shadowed side. In the embedded condition, the left target also appeared lighter than the right one, $t(14) = 15.38$, $p < 0.001$, consistent with both retinal ratios and coplanar ratios.

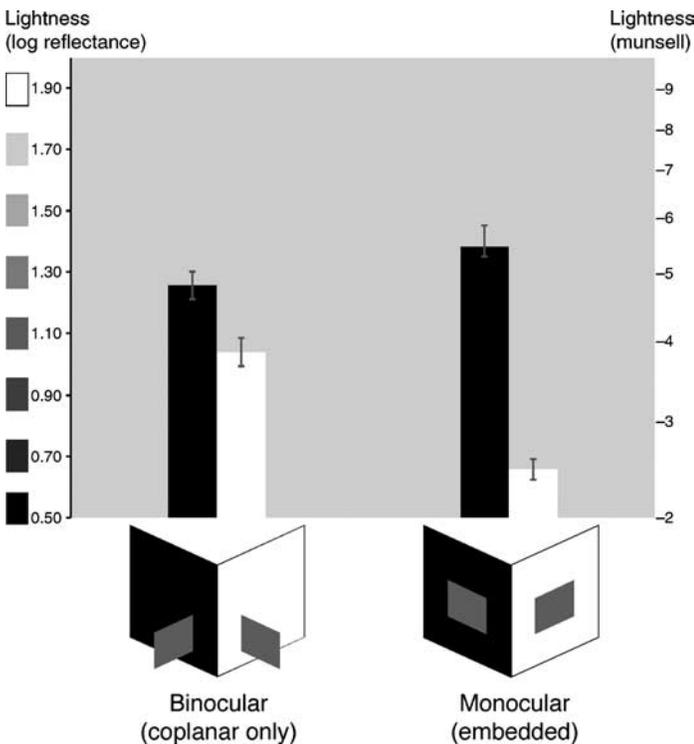


Figure 8. Target lightness in the binocular (coplanar only) and monocular (embedded) conditions. Icons on the X-axis show a perspective view that illustrates the perceived spatial arrangement (not the observer's retinal image) in each condition. The figure follows the same conventions of data presentation as Figure 6.

For each target, we can see the effect of the loss of adjacency by comparing the binocular conditions of Experiment 2 (adjacent and coplanar condition), in which each target was adjacent to its coplanar neighbor, and Experiment 3 (coplanar only condition), in which the target was not adjacent to its coplanar neighbor (Target \times Experiment interaction, across binocular conditions, $F(1,33) = 57.09$, $p < 0.001$). The left target appeared nearly black (Munsell 2.85; 0.74 log reflectance) in the adjacent and coplanar condition, but middle gray (Munsell 4.9; 1.26 log reflectance) in the coplanar only condition, $t(33) = 6.24$, $p < 0.001$. The right target appeared light gray in the adjacent and coplanar condition (Munsell 7.6; 1.69 log reflectance) but dark gray in the coplanar only condition (Munsell 3.9; 1.04 log reflectance), $t(33) = 6.60$, $p < 0.001$. These findings confirm that adjacency is required, in addition to coplanarity, for the robust depth effect found in Experiment 2, a conclusion that is consistent with the smaller depth effect we got in our unarticulated (pilot) version of Kardos.

Our findings are consistent with those of He and Nakayama (1992, 1994), according to which the visual system prefers to make comparisons within a continuous group of surfaces, rather than then across open space. As this finding is replicated in many different domains (texture, motion, visual search, attention; reviewed in Nakayama, He, & Shimojo, 1995), it is not surprising that it also applies to lightness.

This makes logical sense: surfaces that lie within the same plane may or may not be equally illuminated. When surfaces within a plane are adjacent, they form a continuous pattern that will reveal any change of illumination by a visible penumbra on that pattern. However, when coplanar surfaces are separated by a gap, the penumbra can fall within the gap, leaving the change undetected. Furthermore, as suggested by our findings from the Kardos experimental setup (small disk condition; pilot data), the likelihood of this outcome increases as gap width increases. In addition, we find many reports in the literature showing that, for a test patch and an inducing patch floating in midair or embedded in darkness, the degree to which the lightness of the test patch can be predicted by the luminance ratio between the two patches is inversely proportional to the size of the gap between them (Fry & Alpern, 1953; Gogel & Mershon, 1969; Leibowitz et al., 1953; McCann & Savoy, 1991; Newson, 1958).

It should be noted, however, that the loss of adjacency did not entirely eliminate the effect of coplanarity. Had that occurred, the results for the two conditions of this experiment, reflecting only a retinal ratio effect, would have been identical. Instead we see that the right target appeared significantly lighter when it was perceived to float in front of the lighted white side of the display, in the binocular condition, than when it appeared to lie embedded in it, in the monocular condition ($t(28) = 5.02$, $p < 0.001$; Target \times Condition interaction $F(1,28) = 26.48$, $p < 0.001$). For the left target, the difference in lightness when it appeared to

float in front of the black side of the display, in the binocular condition, and when it appeared to lie embedded in it in the monocular condition was marginally significant, $t(28) = -1.99$, $p = 0.056$ (see [Figure 8](#)).

The insulation effect

The larger change in lightness across viewing conditions for the right target appears consistent with a phenomenon labeled insulation. Gilchrist et al. (1999) found that the dramatic compression of the lightness range produced when a row of five squares, covering the whole range of grays, is presented in a spotlight (the staircase Gelb display) is eliminated by surrounding the squares with a coplanar white border (i.e., a coplanar border equal to the highest luminance within the group).

The lightness match we obtained for the right target in the embedded condition occurred under analogous conditions. Note that in the embedded condition, the right target, which was totally surrounded by the brightly illuminated white background, appeared practically black (Munsell 2.5 or 0.66 log reflectance). This is significantly darker than the right target in the monocular condition of [Experiment 2](#), which was not insulated but shared one edge with the shadowed side of the display, $t(33) = 3.98$; $p < 0.001$.

The significant increase in target lightness when the right target appeared to float in front of its high-luminance background in the coplanar only condition suggests that the insulation effect can be also eliminated by depth displacement.

This is in agreement with results obtained by Gilchrist and Radonjić (2007) who studied whether the insulation effect can be modulated by varying the depth of the insulating high-luminance border relative to the group of surfaces it is retinally surrounding. In their experiment, a staircase Gelb display, consisting of five squares of different reflectance spanning the whole range of grays from black to white, arranged in reflectance order, was presented in a spotlight. Using a Munsell chart, separate groups of observers judged the lightness of each of the 5 squares when the display was retinally surrounded either by (1) a coplanar white brightly illuminated border (the coplanar condition), (2) an equally bright border positioned behind the display in a different depth plane (the remote condition), or (3) a low-luminance border, equiluminant to the black paper in the spotlight, positioned behind the display (control no-insulation condition). They found that when the high-luminance border lies in a different depth plane than the surfaces it is retinally surrounding most of the insulation effect obtained with the coplanar border is eliminated: all squares darker than white were perceived as significantly lighter in the remote than in the coplanar condition (for up to 2 Munsell units) with light gray and middle gray squares appearing as light as in the no-insulation condition.

Note that the significant lightening of the black square in the remote condition (when compared to the coplanar condition) corresponds to the lightening of the right target

floating in front of the brightly illuminated background in the coplanar only condition (when compared to the embedded condition).

Experiment 4: Can surroundedness substitute for adjacency?

Given the necessity of adjacency, then, why were we able to obtain such strong depth effects in our replication of Kardos? Apart from articulation, one important difference between the experimental arrangements in the two studies is that in the Kardos replication, the target, while not adjacent to its coplanar neighbor, is nevertheless completely surrounded by it.

This implies that surroundedness might substitute for adjacency. This is a logical extension of the argument that breaking adjacency undermines the depth effect on lightness by allowing a spatial change in illumination (i.e., a penumbra) to fall, unobserved, within the gap. When the coplanar neighbor completely surrounds the target, an illumination border will be hidden only if it falls exactly within the gap, a highly coincidental, unlikely outcome.

To test whether surroundedness can substitute for adjacency, in [Experiment 4](#) we extended each side of the display so that it surrounded its coplanar, yet non-adjacent target (coplanar and surrounded condition). If surroundedness has such an effect, we would expect results more similar to the coplanar and adjacent (binocular) condition of [Experiment 2](#); if not, we would expect results more similar to the coplanar only condition of [Experiment 3](#).

Methods

[Experiment 4](#) was equivalent to [Experiment 3](#) in all respects except that the display was modified so that a coplanar surround was added to each target, one plane at a time. In each condition, one side of the dihedral display was extended to create a 1.7 cm-wide border surrounding the coplanar floating target, as can be seen in [Figure 9](#). The square-shaped border had an outer edge of 11 cm on a side, and an inner edge of 8 cm on a side, with a gap between target and border of about 2 cm.

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

Results and discussion

In both the coplanar and adjacent condition and the coplanar only condition (binocular conditions of

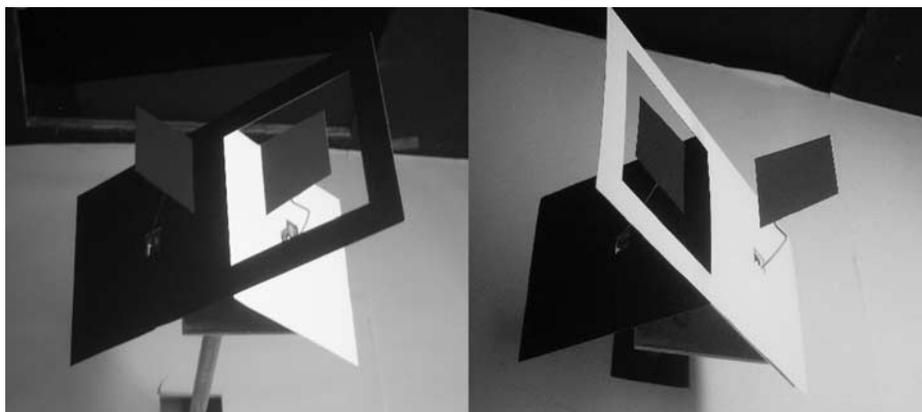


Figure 9. Stimulus setup in Experiment 4, view from the bottom (left) in the bright surround and (right) dim surround conditions; not equivalent to the observer's view.

Experiments 2 and 3), the same group of observers judged the lightness of both targets within each condition. However, in the coplanar and surrounded condition (Experiment 4), the lightness of each target was judged by a separate group of subjects; for technical reasons, we could only surround one target in the display at a time. In order to compare the three conditions statistically, we converted the within-subjects measurements from the coplanar and adjacent and the coplanar only conditions into between-subjects measurements by using only the first of the two targets matched by each observer. In other words, we recomputed the mean lightness of the upper/left target by taking only the matches from one half of the observers and the lightness of the lower/right target by taking only the matches from the other half of the observers in each condition. The new means thus obtained, which are practically identical to those obtained when all matches are used in Experiments 2 and 3, are plotted in Figure 10 together with the mean lightness matches for the targets in the coplanar and surrounded condition.

Halving the total number of observer matches within a condition in this way (to 10 per target in the coplanar and adjacent condition, and 8 and 7 for the right and left targets, respectively, in the coplanar only condition) reduced the power of our statistical tests but allowed us to compare target lightness across conditions and get a valid estimate of the effect of surroundedness.

We found that surroundedness had an effect on lightness, but only in the bright surround and not in the dim surround condition (Target \times Condition interaction, $F(2, 59) = 31.44$, $p < 0.001$; see Figure 10). When the right target was surrounded by the low-luminance border, it appeared dark gray (Munsell 3.4; 0.91 log reflectance) and not significantly different than in the coplanar only condition (Munsell 3.9; 1.04 log reflectance). However, when the left target was surrounded by the high-luminance border, it appeared significantly darker than in the coplanar only condition (Munsell 3.6 or 0.98 log reflectance vs. Munsell 4.8 or 1.25 log reflectance; Tukey HSD, $p < 0.05$) but not as dark as in the coplanar and adjacent condition

(Munsell 2.75 or 0.71 log reflectance; Tukey HSD, $p < 0.05$; main effect of condition for the left target only, $F(2, 32) = 12.62$, $p < 0.001$). On log reflectance scale, the match for the surrounded left target fell precisely midway between its value in the coplanar only condition and its value in the coplanar and adjacent condition. Thus, in the bright surround condition the effect of surroundedness compensated for only half of the effect of adjacency.

These results are in agreement with those in our replication of Kardos (1934) in Experiment 1. However,

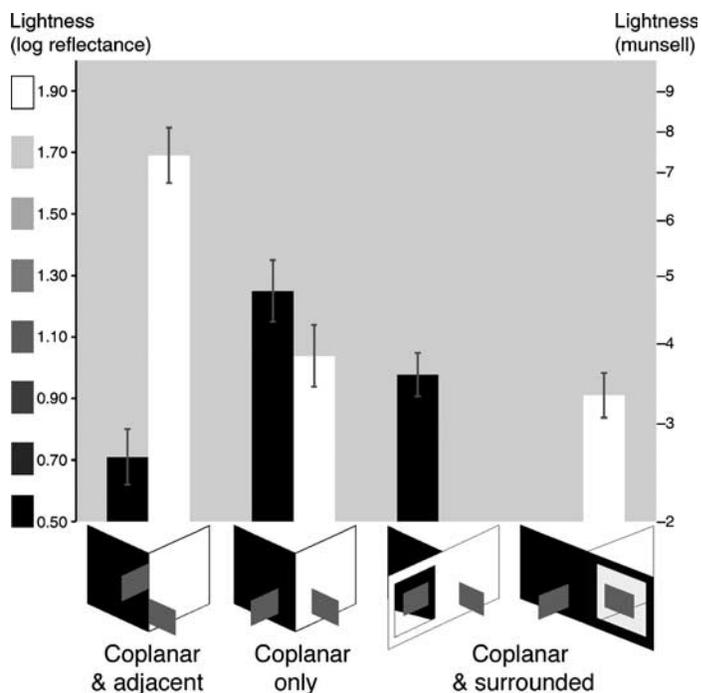


Figure 10. Target lightness in the coplanar and adjacent, coplanar only, and coplanar and surrounded (bright and dark surround) conditions. A perspective view that illustrates the perceived spatial arrangement (not the observer's retinal image) in each condition is shown on the X-axis. The figure follows the same conventions of data presentation as Figure 6.

they suggest that, had we placed the low-luminance dimly illuminated black panel (with an aperture) in the near plane and the high-luminance brightly illuminated white panel in the far plane, we would not have gotten the depth effect.

This asymmetry in the effect of the bright surround and the dim surround is also consistent with the insulation phenomenon mentioned in relation to the right target in the embedded condition of [Experiment 3](#). We noted above that the gamut compression in the staircase Gelb effect is eliminated when the squares are surrounded by a white (highest luminance) border. However, the compression is not eliminated by a black border (Gilchrist, 2006; Gilchrist et al., 1999). Note however that the insulation effect per se cannot explain the absence of the surroundedness effect in the dim surround condition, because the target in the dim surround condition, being in a different depth plane than its high-luminance background, cannot be considered insulated (see [Experiment 3](#); discussion of the insulation effect).

While we obtained a depth effect of 4.4 Munsell steps in our replication of Kardos, we found a depth effect of only 1.9 Munsell steps under analogous conditions using the perpendicular planes arrangement, that is, comparing the bright surround condition of [Experiment 4](#) with the right target embedded in its shadowed retinal background in [Experiment 3](#) (embedded condition).

There are three possible reasons for this difference:

1. In our Kardos replication, we simulated a between-planes illumination ratio of 86:1 while that simulated in our perpendicular planes conditions was only 30:1.
2. The area of the surrounding white panel in [Experiment 1](#) was much larger, both in perceived and in retinal terms, than the area of the surrounding border in [Experiment 4](#).
3. While homogenous (i.e., not articulated) in our perpendicular planes arrangement, in our Kardos replication the target's dark retinal background was highly articulated, containing a number of rectangular gray patches.

All three of these factors have been shown in previous research to increase the depth effect. Katz (1935) first reported higher degrees of constancy (equivalent to a larger depth effect) when each field of illumination (here equivalent to a plane) was both larger and more articulated. Schirillo and Arend (1995) found a larger depth effect using articulated planes compared to an almost identical earlier experiment by Schirillo et al. (1990) with unarticulated planes. Finally, as we show in our Kardos replication, high articulation of the shadowed background is necessary for obtaining the large depth effects in the absence of adjacency.

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 4](#) together with those of the original Kardos (1934) study and our replication in

[Experiment 1](#) reinforce the empirical fact, consistent with the basic premise of the anchoring theory of lightness (Gilchrist et al., 1999), that the highest luminance within an image is treated as special by the visual system.

General discussion

Consistent with the findings of Gilchrist (1977, 1980) and the coplanar ratio principle, our results show that when a target surface has an adjacent neighboring surface that is perceived to lie in the same plane, its lightness is determined based on coplanar, not retinal, luminance ratios. When the adjacency between coplanar surfaces is disrupted, most, but not all, of this effect of coplanar ratios is eliminated. However, the results of our [Experiment 4](#) and our replication of the Kardos original study show that surrounding the target by a non-adjacent but coplanar, high-luminance surface can partially substitute for adjacency in the depth effect on lightness.

The role of articulation in the depth effect

The depth effect in the absence of adjacency originally found by Kardos was small and his research, pioneering as it was, had several methodological weaknesses. Our replication, using a similar experimental arrangement and better controls, shows that depth can have a *large* effect on lightness in the absence of adjacency between the target and its coplanar surround, contrary to the earlier claim by Gilchrist (1977). These large depth effects were produced by (1) surrounding the non-adjacent target, (2) using a between-subjects comparison, and most importantly (3) articulating the shadowed plane.

A number of studies in the literature suggest that articulation, that is, complexity of the stimulus as defined here as the number of surfaces within a field or framework, can significantly affect target lightness (Adelson, 2000; Gilchrist et al., 1999; Katz, 1935). Specifically, the anchoring theory of Gilchrist et al. (1999) predicts that adding articulation to the shadowed plane in the Kardos experimental setup would lighten the back disk coplanar to it, and, thus, increase the depth effect.

Consistent with this prediction, we found that articulation primarily affected the back disk (whose lightness increased from 4.4 to 7.15 Munsell units solely due to the increase in articulation of its coplanar shadowed background) with little effect on the front disk (2.7 vs. 3.1; first presentations only).

This finding, showing that the depth effect is expressed mainly by the shadowed target, is also consistent with the findings of Radonjić, Escobar, Ivory, and Gilchrist (2008) who, in a replication of Gilchrist's (1977) experiment in which the depth planes were articulated, showed that the

depth effect increase with articulation is due to the lightening of the target coplanar with the shadowed depth plane, while the target coplanar with the lighted plane does not change. According to the anchoring theory, this is because, in the shadowed plane, the lightness of the target in relation to the highest luminance in that plane (local framework) is very different than its lightness in relation to the highest luminance in the whole display (global framework). However, for the target in the lighted plane, the local and global highest luminances are the same, thus, increasing the weight of the local framework through articulation would produce little effect.

The role of adjacency and surroundedness in the depth effect

We systematically tested the effect of adjacency and surroundedness on the depth effect on lightness, while keeping coplanar relations constant using a version of the perpendicular planes arrangement of Gilchrist (1977), which features homogenous planes. We found that, when the planes are not articulated, adjacency is necessary for large depth effects: disrupting the adjacency between coplanar surfaces eliminates most, but not all, of the depth effect obtained with adjacent coplanar surfaces. We replicated and quantified the effect of surroundedness in the absence of adjacency: in the lighted plane, half of the depth effect that was lost due to the loss of adjacency was restored when the target was completely surrounded by a non-adjacent, coplanar, high-luminance surface.

Our findings, however, reveal a curious asymmetry, which could not be predicted, either from the work of Kardos or from the previous literature—and still remains to be explained: the substitution of surroundedness for adjacency appears to be effective only in the lighted plane, not in the shadowed plane.

Grouping by illumination hypothesis

We believe that our results can be best understood using a *grouping by illumination hypothesis*. According to this hypothesis, previously implied in Koffka's (1935) principle of belongingness, Gilchrist's (1980) coplanar ratio principle, and more recently, in anchoring theory (Gilchrist, 2006), the visual system computes surface lightness by grouping together surfaces in the image that are equally illuminated, comparing the luminance of surfaces within the group, and mapping the relative luminance values onto the gray scale using anchoring rules (Gilchrist et al., 1999). With few exceptions, groups of surfaces that are surrounded by depth boundaries and/or penumbræ share a common illumination level. We propose that the visual system exploits this property of ecological optics.

According to the grouping by illumination hypothesis, coplanarity is an important factor in lightness computation

because surfaces that lie in the same plane and are facing the same direction are usually equally illuminated. The effect of coplanarity will be the strongest when a group of coplanar surfaces are adjacent, forming a continuous larger surface because in that case any spatial change in illumination will be revealed by a visible penumbra. However, when surfaces in an image are separated by a gap, it is possible that a penumbra falls, undetected, within this gap. In this case, there is not enough information within an image to signal whether the coplanar non-contiguous surfaces belong to the same or different fields of illumination, and this uncertainty increases as the size of the gap increases. Thus, it is logical that the strength of grouping for lightness computation weakens when adjacency is eliminated, as we found in Experiment 3. However, when the target is completely surrounded by another coplanar but not adjacent surface, it would be highly coincidental for a penumbra to fall just within this gap. Thus, in this case the coplanar grouping for lightness computation will be stronger than when the target is floating in a plane without an adjacent coplanar neighbor (as we obtained in the coplanar only condition of Experiment 2) but weaker than when the target is part of a continuous group of surfaces (as we obtained in both the Kardos and the perpendicular planes setups, i.e., Experiments 1 and 4). Overall, in keeping with the grouping by illumination hypothesis, our findings suggest that the strength of grouping is proportional to the degree of certainty with which the visual system can estimate illumination conditions across space.

Grouping by illumination vs. other theoretical approaches

Although our results are consistent with the coplanar ratio principle to the extent that it emphasizes the importance of coplanar relations, the grouping by illumination hypothesis provides a better theoretical framework for understanding the majority of our findings. For example, the effect of surroundedness (Experiments 1 and 4), as well as the modest effect of coplanarity in the absence of adjacency (Experiment 3), contradicts the adjacency requirement of the coplanar ratio principle.

In addition, while the coplanar ratio principle proposed by Gilchrist (1980) treated planarity as an all-or-none variable, the grouping by illumination hypothesis suggests a graded view of planarity, which is more consistent with the results of a number of previous studies (Gogel & Mershon, 1969; Wishart, Frisby, & Buckley, 1997) as well as our own findings. In the coplanar only condition of Experiment 3, the strength of coplanar ratios in determining target lightness is reduced, but not eliminated, when the target is not coplanar with its retinal background, but appears to float in front of it in a different plane. The graded interpretation of coplanarity is also consistent with the hypothesis proposed by Gilchrist and Radonjić (2006) according to which surfaces that are parallel and facing

the same direction are (perhaps weakly) grouped for lightness even if they are not immediately adjacent or coplanar. Indeed, the grouping by illumination hypothesis can be understood as a more general principle that integrates this *relaxed* version of the coplanar ratio principle.

A group of surfaces treated by the visual system as sharing a common illumination level is roughly equivalent to the notion of a framework in the anchoring theory (Gilchrist et al., 1999).

Across experiments, we obtained strong effects of perceived depth on lightness with either minimal (Experiment 1) or no change in the retinal image (Experiments 2 and 3). Thus, any lightness account that is strictly based on the processing of the retinal image, such as classic local contrast accounts that favor lateral inhibition (Cornsweet, 1970; Jameson & Hurvich, 1964) or recent, more sophisticated spatial filtering models, such as the ODOG model of Blakeslee and McCourt (1999, 2003) or the model of Robinson, Hammon, and de Sa (2007) fail to account for our data.

Our results are, in general, consistent, with a number of more recent studies showing the perceived three-dimensional arrangement plays a significant role in lightness perception (Bloj et al., 2004; Bloj, Kersten, & Hurlbert, 1999; Boyaci, Doerschner, & Maloney, 2006; Boyaci, Maloney, & Hersh, 2003; Ikeda, Shinoda, & Mizokami, 1998; Knill & Kersten, 1991; Logvinenko & Menshikova, 1994; Pessoa, Mingolla, & Arend, 1996; Ripamonti et al., 2004; Spehar, Gilchrist, & Arend, 1995; Taya, Ehrenstein, & Cavonius, 1995).

According to Boyaci, Doerschner, and Maloney (2004; Boyaci et al., 2003) and Bloj et al. (2004; see also Ripamonti et al., 2004), in order to judge surface lightness the visual system first creates an illumination model in a given scene in terms of intensity, chromaticity, and spatial variation, based on cues to the illumination available in the image (Boyaci et al., 2006; Maloney, 2002) and then removes the illumination component from luminance, to derive surface lightness. This “discounting the illuminant” hypothesis, similar to the classic Helmholtz’s (1868/1924) idea of inferring the illumination, differs from the “grouping by illumination” hypothesis in its requirement that parameters of the light source, such as intensity and direction, must be explicitly estimated by the visual system, a requirement we regard as computationally expensive.

Ikeda et al. (1998; see also Cunthasaksiri, Shinoda, & Ikeda, 2004) propose a similar account, according to which, based on information available in the retinal image, the visual system constructs three-dimensional regions of illumination (Recognized Visual Space of Illumination, RVSI) and then uses the properties of this space (intensity, chromaticity) to judge the lightness and color of surfaces within that space. Ikeda et al. thus propose an interesting idea that the visual system tends to compare surfaces within a volume of three-dimensional space, not within a plane. However, it seems to us that the RVSI hypothesis would have predicted a stronger effect of

surroundedness in both coplanar and surrounded conditions of Experiment 4, because one would assume that the target is a member of the same RVSI as the surrounding border.

We believe that, overall, the pattern of results we report can be best understood by the assumption that the visual system computes lightness by grouping together surfaces in the image that are equally illuminated, comparing the luminance values of surfaces within the group, and mapping these relative luminance values onto the gray scale using anchoring rules. However, in any case, our study contributes to an understanding of the conditions under which target lightness changes with a change in spatial relations and provides data that need to be accounted for by any comprehensive theoretical account of lightness computation in complex three-dimensional scenes.

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