Lightness perception in simple images: Testing the anchoring rules

Ana Radonjić Department of Psychology, University of Pennsylvania, Philadelphia, PA, USA

Alan L. Gilchrist Department of Psychology, Rutgers University, Newark, NJ, USA

One approach toward understanding how vision computes surface lightness is to first determine what principles govern lightness in simple stimuli and then test whether these hold for more complex stimuli. Gilchrist (2006) proposed that in the simplest images that produce the experience of a surface (two surfaces differing in luminance that fill the entire visual field) lightness can be predicted based on two anchoring rules: the highest luminance rule and the area rule, plus a scale normalization. To test whether these anchoring rules hold when critical features of the stimuli are varied, we probed lightness in simple stimuli, painted onto the inside of hemispheric domes viewed under diffuse lighting. We find that although the highest luminance surface appears nearly white across a large variation in illumination (as predicted by the highest luminance rule), its lightness tends to increase as its luminance increases. This effect is small relative to the size of the overall luminance change. Further, we find that when the darker region fills more than half of the visual field, it appears to lighten with further increases in area but only if it is a single surface. Splitting the dark region into smaller sectors that cover an equal cumulative area diminishes or eliminates the area effect.

Introduction

Lightness, or the perceived shade of gray of a surface, is a perceptual quality that corresponds to its physical reflectance, which is the proportion of incident light the surface reflects. A typical white surface, for example, reflects ~90% of incident light, whereas a typical black surface reflects ~3%.

Identifying the shade of gray of a surface feels easy and effortless in most natural viewing situations. To accomplish this, however, the visual system needs to solve a challenging computational problem. The luminance, or light intensity reflected from an object's surface to the eye, depends both on surface reflectance, which is a stable property of an object, and incident illumination, which in natural viewing varies widely over time and space. The processes that underlie our ability to maintain a relatively stable perception of surface lightness despite large variations in illumination and viewing conditions are not well understood.

One approach in studying mechanisms that support lightness perception is to first establish which principles govern lightness in simple stimuli and then test whether the same principles generalize to more complex stimuli.

The simplest stimulus that supports surface perception requires that at least one edge is present in the visual field. If there are no edges (i.e., a Ganzfeld), no surface is perceived, only an infinite fog (Metzger, 1930). Thus, the simplest stimulus for studying lightness consists of two surfaces of differing luminance that fill an observer's entire visual field. Gilchrist and his collaborators have extensively used such stimuli to study lightness and proposed that in simple images, lightness depends on three main principles: the highest luminance rule, the area rule, and scale normalization (Gilchrist, 2006).

Scale normalization is a scaling rule that specifies how the stimulus luminance range maps onto the range of perceived grays. It asserts that the visual system tends to adjust the range of perceived lightness values toward the canonical reflectance range of 30:1—from typical white to typical black. This normalization is manifested as the expansion of the perceived lightness range when the luminance range in the stimulus is much smaller than 30:1 and/or the compression of the perceived lightness range when the luminance range is much larger.

The highest luminance rule and area rule are anchoring rules; they establish the anchor point for

Citation: Radonjić, A., & Gilchrist, A. L. (2014). Lightness perception in simple images: Testing the anchoring rules. *Journal of Vision*, *14*(13):25, 1–13, http://www.journalofvision.org/content/14/13/25, doi:10.1167/14.13.25.

doi: 10.1167/14.13.25 Received April 3, 2014; published November 25, 2014 ISSN 1534-7362

mapping stimulus luminance onto the perceived lightness scale. According to the highest luminance rule, the highest-luminance surface in a simple image is mapped to white (~90% reflectance), and surfaces lower in luminance are scaled relative to that highest luminance based on the ratio principle (Wallach, 1948) when the luminance range in the image is ~30:1 and scale normalization when it is not. For example, based solely on the ratio principle, a surface that is half as bright as the highest luminance should appear light gray (45% reflectance).

The empirical evidence in support of the highest luminance rule comes from critical experiments conducted by Li and Gilchrist (1999). These experiments pitted the hypothesis that the highest luminance surface serves as an anchor (Newson, 1958; Land & McCann, 1971; Marr, 1982; Horn, 1986) against the average luminance hypothesis (also known as the gray-world assumption), according to which the anchor is the mean image luminance, which appears middle gray (Helson, 1964; Buchsbaum, 1980). Li and Gilchrist used a set of simple stimuli, each consisting of two surfaces—one black, another middle gray (3.1% and 24.6% reflectance, respectively)—painted onto the inside of a large, diffusely illuminated hemispheric dome. The observer's head was placed inside the dome so that the interior of the dome filled the entire visual field. Consistent with the highest luminance hypothesis, they found that observers perceived the middle-gray surface as white (ranging from Munsell 8.9 to 9.5) and the black surface as middle gray.

The results of this study also suggested that relative surface area plays a role in the luminance-to-lightness mapping: As the black surface got larger, it also appeared lighter. Gilchrist and Radonjić (2009) provided systematic evidence for the area effect on lightness in simple images by probing lightness in a set of dome stimuli in which the relative area of a radial dark-gray sector (reflectance 7.7%) systematically increased relative to a light-gray sector (reflectance 36%) as the central angle of the darker sector increased from 11° to 354°. They found that the darker sector appeared lighter as its area increased, whereas the appearance of the lighter sector did not change. Furthermore, the area had a strong effect on the dark sector lightness only when the darker sector covered more than half of the visual field. Occasionally, we do find evidence of the area effect on lightness even when the dark sector covers less than half of the visual field, but these effects typically tend to be smaller.

To make accurate predictions about lightness computation in complex images based on the rules revealed by simple stimuli, it is necessary to establish the stability of these rules under a wide range of conditions. To this end, we designed a study that examined the validity of the two anchoring rules—the highest luminance and the area rule—when critical features of the stimuli are varied.

In Experiments 1 and 2, we tested whether the highest luminance rule holds across a large variation in illumination (the absolute luminance) of a stimulus. In Experiment 3, we explored whether the area effect on lightness depends on the area of a single dark sector or the cumulative dark area in the stimulus. In other words, we asked whether splitting the area of a darker sector that covers more than half of the visual field into smaller sectors equal in cumulative area modulates the area effect on lightness.

General method

Stimuli

Each stimulus consisted of a pattern of radial sectors of different shades of gray that were spray-painted onto the interior of a large opaque acrylic hemisphere (the dome; 76 cm in diameter). Sector reflectance, size, and number were varied across the experiments.

Apparatus

The dome was suspended in a rectangular diffusing chamber. The illumination came from two 750-W halogen bulbs housed in a metal box attached to the back of the chamber (for a detailed description of the apparatus, see Gilchrist & Radonjić, 2009). Diffuse, homogenous illumination thus entered the dome around its entire perimeter. The exterior of each dome was painted matte white to maximize interreflections in the diffusing chamber.

A pair of sliding metal shutters was installed at the aperture connecting the illumination box to the chamber. By controlling the size of the aperture via the sliding shutters, the illumination intensity in the dome could be controlled with precision over a wide range without any change in color temperature.

The observer viewed the dome by pressing his or her head into a hockey mask recessed into the center of the front wall of the diffusion chamber. In this position, the observer's eyes were located within the suspended dome, at approximately 22 cm from its interior surface, so that the stimulus pattern filled the entire visual field.

The position of each dome in the apparatus was fixed across conditions and observers. Stimulus icons (Figures 1–3) depict the orientation of each stimulus pattern in the dome apparatus.

Illumination level

In the standard condition, the illumination in the dome was adjusted so that the luminance of the lighter sector was equal to the luminance of a piece of white paper attached to the front of the diffusion chamber when the room lights were on. Because the luminance of the lighter sector under standard illumination was equated by eye separately for each experiment, the exact luminance values varied slightly. We report stimulus luminance values, measured using a Konica Minolta LS-100 luminance meter, for each experiment and condition.

Procedure

The observer listened to the experimental instructions in the laboratory, which was darkened except for the bulb illuminating the Munsell chart. We used instructions identical to those in the previous study (for verbatim instructions, see Gilchrist & Radonjić, 2009). Briefly, the observer was asked to place his or her head into the hockey mask and, once the lights in the chamber were turned on, to look straight ahead. The task was to memorize the two shades of gray that appeared in the dome. When the observer confirmed that the shades had been memorized, the experimenter turned the chamber lights off, and the observer moved from the dome apparatus to the Munsell chart and proceeded to make matches. The observer had unlimited time to look at the stimulus while in the dome but was not allowed to look back again once the dome lights were turned off.

Matching chart

Observers matched the lightness of the dome sectors using a 16-step Munsell chart. This chart consisted of Munsell grayscale paper samples arranged in ascending reflectance from black (N 2.0/; nominal reflectance 3.1%) to white (N 9.5/; nominal reflectance 90%; luminance 317 cd/m^2) against the white background (reflectance ~84%). The chart was housed in a metal chamber, which was mounted on the wall to the left of the apparatus and separately illuminated by a 22-W florescent tube.

Observers

A total of 532 observers participated in the study: 83 in Experiment 1, 325 in Experiment 2, and 124 in Experiment 3. In each experiment, a separate group of about 20 observers viewed each dome stimulus in each condition and judged the lightness of the two dome sectors. All observers were unpaid volunteers. They were students of Rutgers University, some of whom received course credit for their participation. The experimental protocols were approved by the Institutional Review Board of Rutgers University and were in accordance with the World Medical Association Helsinki Declaration (October 2008).

Criteria for exclusion

In each condition, the observer's matches were identified as outliers and excluded from further analysis if one of their matches fell more than three standard deviations from the condition mean, as computed with the potential outlier excluded. Large deviations from the mean for some observers may be due to their failure to understand or follow experimental instructions (e.g., they moved their head in and out of the apparatus before making a match, while the dome lights were still on). The empirical exclusion criterion is established because the experimenter, being positioned in the back of the diffusing chamber, was not able to monitor the observer's behavior while the dome lights were on.

In addition, one observer, who matched the dark and light sector lightness to the same Munsell chip, was excluded from Experiment 3 (270° bisectored dome). The total number of observers and outliers in each condition of each experiment is shown in Appendix A (Table A1).

Data analysis

We converted the lightness matches from Munsell values to log % reflectance (base 10) and used these values in further analysis. For each experiment and condition, the result figures plot the mean lightness match (over observers) for each dome sector in log % reflectance. When appropriate, we provide mean matches in Munsell values as a reference for readers familiar with the Munsell scale. Table A2 in Appendix B shows the match mean and standard deviation for each dome sector in both Munsell and log % reflectance units for all experiments and conditions.

For each condition, we estimated the reliability of the data via a bootstrap procedure. For each dome stimulus sector in each experimental condition, we resampled (with replacement) a new set of matches of the same size from the set of actual matches and computed mean sector lightness from the resampled data. In all plots of the results, error bars represent the 95% confidence interval computed over 2,000 iterations of the resampling (Efron & Tibshirani, 1993).

Experiment 1

To test whether the highest luminance rule holds across a wide range of absolute stimulus luminance values, in Experiment 1 we measured the perceived lightness of the two sectors in a bipartite dome while varying the illumination intensity. We probed lightness across four illumination levels, spanning a total range of 58:1 (1.76 log units). In each illumination condition, a different group of observers viewed the dome stimulus and judged the lightness of the two sectors.

According to the highest luminance rule, the lighter dome sector, which has the highest luminance, should appear white or close to white, and its lightness should not change as its luminance varies across the four illumination levels. The lightness of the darker sector should depend primarily on the ratio of its luminance relative to the lighter sector, although the relative area and the scale normalization could also have some effect. Nevertheless, as these factors remain constant across illumination conditions, the lightness of the dark sector should remain roughly constant as well.

Method

Stimulus

The dome stimulus consisted of two sectors of different shades of gray, each covering half of the dome (split vertically; see stimulus icon in Figure 1). The right sector was painted black (reflectance 4.6%, matched to Munsell sample N 2.5/), and the left one was painted dark gray (reflectance 8.6%; matched between Munsell samples N 3.25/ and 3.5/), yielding a light/dark reflectance (luminance) ratio of ~1.9:1.

Illumination levels

We varied illumination across four levels roughly equally spaced on a log scale, spanning a linear range of 58:1. The measured luminance of the lighter dome sector in the four illumination levels was 24.25 (the standard condition), 5.95, 1.56, and 0.42 cd/m^2.

Results

Figure 1 shows mean the lightness matches for each dome sector across four illumination levels, with error bars representing bootstrapped 95% confidence intervals.

We examined the effect of overall luminance variation on sector lightness via a two-way analysis of variance (ANOVA) with sector reflectance (dark vs. light) as a within-subject factor and illumination level

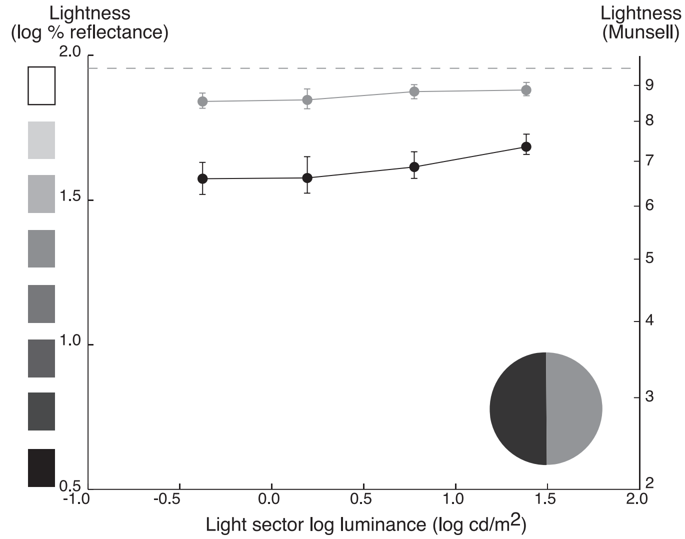

Figure 1. Experiment 1 results. Mean lightness matches for the light sector (in gray) and dark sector (in black) across four levels of dome illumination. Error bars represent bootstrapped 95% confidence intervals. The y-axis shows lightness in log% reflectance. For readers more familiar with the Munsell scale, we indicate the corresponding Munsell value on the right y-axis. An icon illustrating the stimulus is shown at bottom right. The horizontal dashed line across the graph indicates the reflectance of a typical white surface (90%; Munsell N 9.5/). Gray shades used for stimulus icon and the log % reflectance scale are chosen for illustration purposes only and may not correspond to actual reflectance values.

(four levels) as a between-subject factor. We found main effects of both reflectance, $F(1, 75) = 499.56$, $p < 0.001$, and illumination level, $F(3, 75) = 3.57$, $p < 0.05$, as well as a marginally significant Reflectance × Illumination Level interaction, $F(3, 75) = 2.50$, $p = 0.066$. We further explored this interaction via two separate one-way ANOVAs (one for each sector reflectance) combined with post hoc tests. Because the number of observers across our experimental conditions differed slightly, and because in some experiments we failed to reject the hypothesis that the variance of lightness matches across conditions was homogenous (as shown by Levene's Test of Equality of Variance), we used Tamhane's post hoc test to assess changes in sector lightness across conditions in all experiments.

Consistent with the highest luminance rule, varying the illumination had no effect on the lightness of the lighter dome sector. Despite the large variation in absolute luminance, the perceived lightness of this sector was close to white (mean Munsell match: 8.6–8.9) and roughly constant across conditions, $F(3, 75) < 2$, $p =$ ns.

However, the change in illumination had a significant effect on the lightness of the darker sector, $F(3, 75) = 3.70$, $p = 0.015$, which appeared lighter under the standard than either the lowest or second-lowest illumination levels (Tamhane test, both $p < 0.05$). Nevertheless, this change in lightness was very small relative to the change in luminance; increasing the sector luminance by 1.76 log units caused the perceived reflectance of the sector to increase by only 0.11 log% reflectance, equivalent to three fourths of a Munsell step.

Experiment 2

The goal of Experiment 2 was to replicate the findings from Experiment 1 using a larger stimulus set that had different sector reflectances, a different reflectance range, and a different relative area of the lighter and darker sector. Using higher-sector reflectance also allowed us to explore the effect of illumination (luminance) variation over a larger range. The methods were identical to those of Experiment 1, except for the stimulus differences summarized below.

Stimuli

Three domes were chosen from a set of nine domes that have previously been used to study the effect of relative area on perceived lightness (Gilchrist & Radonjić, 2009). The three domes we chose were the two extremes of relative area: one in which the dark sector was very small (11°), one in which it was very large (354°), and a midpoint in which each sector filled half the dome area (180°, as in Experiment 1).

Dark and light sector reflectance was constant across domes (7.7% and 36%, respectively), yielding a reflectance (luminance) ratio of light to dark sector of 4.7:1. Below, we use the size of the dark sector to denote each dome stimulus (e.g., "11° dome" refers to a dome in which the central angle of the dark sector subtends ~11° whereas the light sector subtends ~349°).

Illumination level

In Experiment 2, the illumination intensity in the dome was varied across five levels roughly equally spaced on log scale, spanning the total linear range of 233:1 (2.37 log units). The luminance of the light sector across conditions was 116.34, 30.27 (the standard condition),[1] 6.66, 1.88, and 0.5 cd/m^2.

For each illumination level, the overall luminance across the three dome stimuli that differed in relative area was equated using dark sector luminance as a reference.

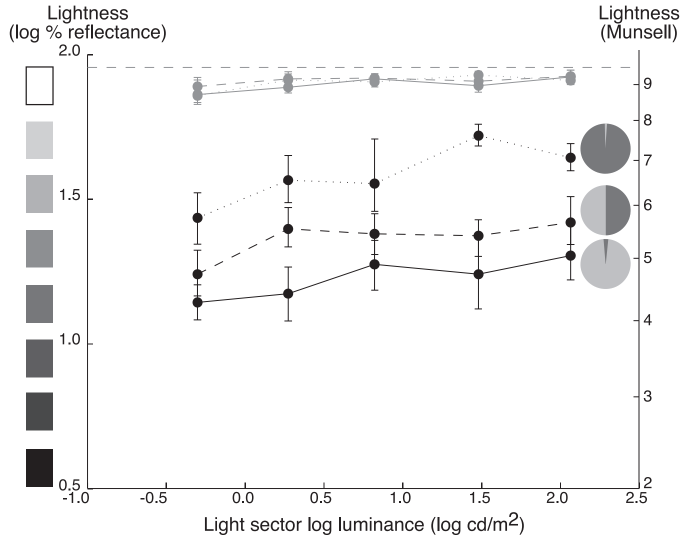

Figure 2. Experiment 2 results. Mean lightness matches for stimuli in which the dark and light sectors cover different relative areas across five levels of dome illumination (5° dark sector dome is shown in solid, 180° in dashed, and 354° in dotted line). This figure follows the same representation conventions as Figure 1. Icons illustrating the stimuli are shown to the right of the corresponding dark sector data.

The luminance of the light sector we report is computed from the dark sector luminance and the reflectance ratio between the dark and the light sector (within an illumination level, the variation across stimuli was up to 4%).

A different group of observers viewed each dome stimulus in each illumination condition.

Results

Figure 2 shows the mean lightness matches across five illumination conditions for each dome stimulus.

A three-way ANOVA with sector reflectance (dark vs. light) as a within-subject factor and illumination level (five levels) and dark sector area (11°, 180°, and 354°) as between-subject factors revealed both Reflectance × Area and Reflectance × Illumination Level interaction (for complete ANOVA results, see Table 1) but no significant Area × Illumination Level or Area × Illumination Level × Reflectance interaction. Therefore, we analyzed the effects of illumination and area on sector lightness separately.

Effect of illumination (luminance)

To further explore the Reflectance × Illumination interaction, we conducted two separate one-way ANOVAs—one for each dome sector—with illumination level as a fixed factor.

Source	Sum of squares	df	Mean square	F	p
Within-subjects effects					
Reflectance	40.42	1	40.42	2171.86	<0.001
Interaction:					
Reflectance × Area	3.26	2	1.63	87.50	<0.001
Interaction:					
Reflectance × Illumination	0.39	4	0.10	5.25	<0.001
Interaction:					
Reflectance × Area × Illumination	0.13	8	0.02	0.89	0.53 (*ns*)
Error (reflectance)	5.51	296	0.02		
Between-subjects effects					
Area	3.45	2	1.73	77.16	<0.001
Illumination	1.12	4	0.28	12.54	<0.001
Interaction: Area × Illumination	0.30	8	0.04	1.68	0.10 (*ns*)
Error	6.62	296	0.02		

Table 1. Results of three-way analysis of variance (ANOVA) for Experiment 2. Dome sector reflectance is analyzed as a within-subject factor, while dark sector area and dome illumination level were between-subject factors. ANOVA modeled the main effects of sector, area, and illumination and their interactions.

Unlike Experiment 1, in Experiment 2 we find that varying the illumination had a significant effect on the lightness of both the light and the dark dome sector: $F(4, 306) = 9.52$, $p < 0.001$, and $F(4, 306) = 5.7$, $p < 0.001$, respectively.

The light sector appeared darker in the lowest illumination condition than in the second-lowest ($p < 0.05$), medium ($p = 0.001$), standard ($p < 0.01$), or high illumination ($p < 0.001$) conditions. Similarly, the dark sector appeared darker in the lowest illumination condition than in the medium ($p < 0.05$), standard ($p < 0.01$), or high illumination conditions ($p < 0.001$). However, we failed to observe a significant change in the lightness of either the dark or light sectors when we contrasted any of the other four illumination levels.

As in Experiment 1, the size of the illumination effect on lightness was very small: increasing illumination by 2.37 log units caused the lightening of the light sector by only 0.05 log % reflectance (½ Munsell step) and of the dark sector by 0.18 log % reflectance (about 1 Munsell step).

Effect of relative area

We analyzed the Reflectance × Area interaction via two separate one-way ANOVAs—one for the dark and one for the light dome sectors—with the area of the dark sector as a fixed factor. We replicated the basic area effect: as the dark sector area got larger, it also appeared lighter, $F(2, 308) = 77.62$ $p < 0.001$, while the light sector did not significantly change, $F(2, 308) = 2.44$, $p = 0.09$.

We find that the dark sector appeared lighter at 354° than at either 11° or 180°, consistent with the area rule (both $p < 0.001$). However, we also observe lightening of the dark sector as its area increased from 11° to 180° ($p < 0.001$), and this upward trend is evident in Figure 2 for all illumination levels.

As discussed earlier, although this finding is not strictly in accordance with the area rule (Gilchrist & Radonjić, 2009), both some of our unpublished work and the work published by others (Kozaki, 1963) have shown that the area can have an effect on dark sector lightness even when the dark sector covers less than half of the visual field. These effects, however, are typically smaller in size, and this is consistent with the finding we report here: confidence intervals for the dark sectors of the 11° and 180° dome are overlapping across most illumination levels, unlike those for the 180° and 354° dome.

Experiment 3: Testing the area rule

In all previous experiments establishing the area effect on lightness, the dark surface was always a single sector, leaving it unclear whether the cumulative dark area in the stimulus or the area of a single dark sector drives this effect.

In Experiment 3, we addressed this question by comparing the area effect in a set of domes that consisted of multiple dark and light sectors (multisectored domes) with a set of domes that matched these in total dark/light area but consisted of just a single dark and light sector (bisectored domes). If the area effect depends on the cumulative area, then the degree of lightening of the dark sector as its area increases should be roughly the same for both multisectored and bisectored domes.

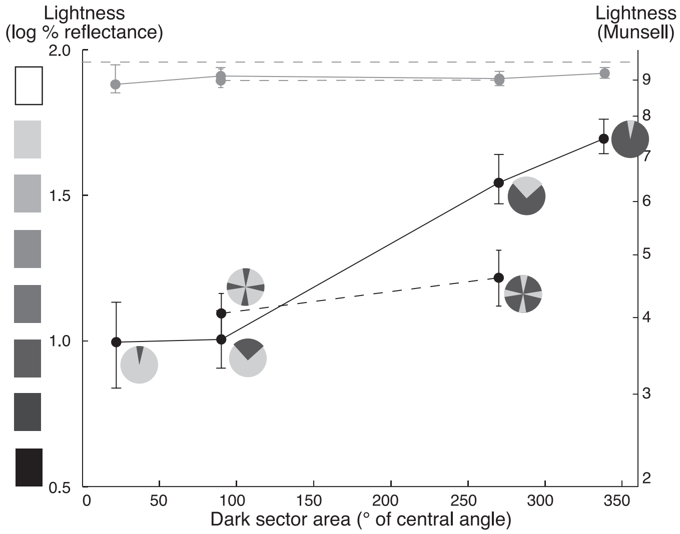

Figure 3. Experiment 3 results. Mean lightness matches for the bisector (solid lines) and multisector domes (dashed lines). The x-axis shows the area of the dark sector. Icons illustrating the dome stimuli are shown at corresponding dark sector area levels. In all other respects, the figure follows the same representation conventions as Figure 1.

Stimuli

The four bisectored domes consisted of a single dark and a single light sector (as in Experiments 1 and 2). Across the four domes, the relative area of the dark/light sector varied, so that the area of the dark sector was 22°, 90°, 270°, or 338°.

The two multisectored domes matched the 90° and 270° bisectored domes in total dark/light area but consisted of four dark sectors alternating with four light sectors (see stimuli icons in Figure 3). Thus, the size of each dark sector was approximately 22° in the 90° multisectored dome and 68° in the 270° multisectored dome (with a single light sector area of 68° and 22°, respectively).

The reflectance of the dark and the light sectors was approximately 7.7% and 51.3%, respectively (matched to Munsell samples N 3.25/ and N 7.5-7.75/) and constant across all stimuli. The stimuli were viewed under standard illumination, and the sector luminance was closely matched across stimuli (lighter sector: 24 cd/m^2; darker sector: 3.6 cd/m^2; up to 4% variation).

Results

The mean sector lightness for each dome averaged across observers is plotted in Figure 3. The figure illustrates three main findings. First, we replicated the area effect for the set of bipartite domes: a two-way ANOVA with sector reflectance (light vs. dark) as a within-subject factor and the dark sector area (four levels) as a between-subject factor revealed a main effect of sector reflectance $F(1, 77) = 495.33$, $p < 0.001$, and area, $F(3, 77) = 41.34$, $p < 0.001$, and a significant Reflectance × Area interaction, $F(3, 77) = 44.30$, $p < 0.001$. The increase in relative area of the dark sector had a significant effect on lightness only for the dark sector, $F(3, 77) = 45.79$, $p < 0.001$, and only when it covered more than half of the visual field (as shown by one-way ANOVA for the dark sector only). In the bisectored domes, the dark sector in the 338° dome appeared lighter than in the 22° ($p < 0.001$), 90° ($p < 0.001$), or 270° ($p < 0.05$), as it did in the 270° dome when compared with either the 22° or 90° domes (both $p < 0.001$); we found no difference, however, in dark sector lightness between the 22° and 90° domes.

Second, the change in relative area of the dark-to-light sector had no effect on the lightness of the light sector, which, consistent with the highest luminance rule, appeared close to white in all bisectored as well as both multisectored domes.

Third, and central to our main question, we found that splitting a single dark sector into four smaller sectors that were equal in total area significantly modulated the area effect on lightness. A two-way ANOVA with the dark sector area (90° vs. 270°) and the number of sectors (two vs. eight) as between-subject factors revealed significant main effects of area, $F(1, 76) = 49.07$, $p < 0.001$, and the number of sectors, $F(1, 76) = 6.28$, $p < 0.05$, on dark sector lightness, as well as a significant Area × Number of sectors interaction, $F(1, 76) = 19.54$, $p < 0.001$.

Dividing a single dark sector into multiple sectors had no effect on its lightness outside the zone in which the area rule applies (the bisectored vs. multisectored 90° dome: $t(36) = 1.38$, $p = 0.18$). However, it caused a significant darkening in the area rule zone, by about 1¾ Munsell steps (bisectored vs. multisectored 270° dome: $t(40) = 4.89$, $p < 0.001$). Further, although each individual dark sector tripled between the 90° and 270° multisectored domes, this increase in area was not sufficient to cause a significant increase in its lightness, $t(37) = 1.86$, $p = 0.07$.

In summary, our findings suggest that area has an effect on dark sector lightness only when a single dark region fills more than half of the observer's visual field.

Discussion

Anchoring theory of lightness (Gilchrist et al., 1999) makes a clear distinction between simple and complex images: A simple image is one in which all the surfaces lie within a single illumination level (a single framework), whereas complex images contain multiple adjacent fields of illumination (multiple frameworks).

According to anchoring theory, in a complex image, perceived surface lightness is a result of codetermination (similar to that proposed by Kardos, 1934). That is, the lightness of a target surface depends both on its lightness value computed within the local framework (surfaces it is immediately grouped with) and its lightness value computed within the global framework (the entire visual field). Within a framework, lightness computation is governed by the anchoring and scaling rules, and we find that rules valid for simple images (the highest luminance rule, the area rule, and scale normalization) apply to frameworks embedded within complex images (for a more detailed description of the theory algorithm, see Gilchrist et al., 1999; Radonjić & Gilchrist, 2013).

Because predicting lightness in complex images critically depends on the rules of lightness computation found in simple images, it is important to specify the range of stimuli across which these rules hold. Therefore, we designed a program of experiments that tested whether the anchoring rules proposed by Gilchrist (2006) accurately predict lightness in simple stimuli when the key stimulus characteristics, such as stimulus luminance (illumination), relative area, and the number of sectors, are varied.

Lightness of the highest luminance surface shows a weak dependence on luminance

To test if the highest luminance rule holds irrespective of variation in overall stimulus luminance in Experiments 1 and 2, we probed sector lightness across a range of illumination levels as wide as our stimuli and experimental setup allowed. Although the stimuli in the two experiments differed in sector reflectance, reflectance range, the relative area of the light and dark sector, and the overall range of illumination variation, the results followed a similar pattern.

Contrary to the predictions of the highest luminance rule, as the stimulus luminance increased, the perceived sector lightness also increased. This effect was slightly more pronounced for the darker sector, for which the size of the overall lightness change was consistently larger than for the lighter sector and the recorded effect reached significance in both experiments.

For both sectors, however, the rate of lightness change was small relative to the rate of the luminance change. For the lighter sector, which was the highest luminance surface, the lightness change was so small that it was difficult to measure reliably when the range of luminance variation was limited. In Experiment 1, we recorded an overall increase in lightness of one third of a Munsell step, indicative of the lightening trend that failed to reach significance. In Experiment 2, the range of luminance variation was sufficiently large to reveal a significant effect, but the size of the lightness change was smaller than one half of a Munsell step when averaged across stimuli and observers.

One potential explanation for the positive slope in our Ganzfeld experiments lies in the concept of temporal anchoring (Cataliotti & Bonato, 2003; Annan & Gilchrist, 2004). Just as lightness appears to represent a compromise between values computed in both the local and global frameworks, so we have found evidence for a compromise between values computed by the current anchor and by the immediately prior anchor. Thus, although the lighter sector is the current highest luminance (and thus computed as white), its luminance may be substantially lower than the highest luminance in the laboratory experienced by the observer prior to entering the dome. Further, the difference between these two luminance levels tends to increase as the illumination level in the dome decreases. A compromise between current and prior anchors, giving very little weight to the prior anchor, would produce a weakly positive slope. Should this interpretation be supported by subsequent experiments, it would suggest that a phenomenon of temporal anchoring, although real, exerts only a very weak effect.

Despite the slope, our results are generally consistent with the prediction that the highest luminance appears white. All of our means for the lighter sector fell between Munsell values of N 8.5/ and N 9.5/. Indeed, we have found that, when handed a piece of Munsell 8.5 paper and asked to report its color, almost all observers call it white.

Further, and related to this issue, comparing the lightness for the highest luminance sector across Experiments 1 and 2 might lead one to conclude that perceived lightness of the highest luminance sector depends on reflectance, as the light sector appeared consistently darker in Experiment 1 in which its reflectance was lower when compared with Experiment 2 (180° dome). We believe, however, that the explanation for this finding lies in the fact that our stimuli were real illuminated surfaces. For such stimuli, perfect stimulus control is practically unattainable. In the dome, when a single stimulus fills one's entire visual field, any stimulus flaws or specks of dust are easily visible and can modulate perceived lightness. For example, a speck of dust on a surface whose reflectance is lower than 90% would appear white and thus lower the perceived lightness of the target surface. The larger the reflectance difference of the target surface from that of white, the more vulnerable it is to such imperfections.

In a recent study Anderson, Whitbread, and de Silva (2014) measured surface lightness across different illumination levels in a more complex stimulus, which consisted of paper samples of varying reflectance arranged in a Mondrian pattern and viewed in a laboratory that was painted completely black. Similar to us, they found that for both real paper-and-illuminant stimuli as well as the simulated version of their stimuli presented on a computer monitor, the perceived lightness of the highest luminance surface increased as the illumination increased. In contrast to our study, they report (a) a considerably larger shift in lightness as a function of luminance than the one we found and (b) that the highest luminance surface appeared as dark as middle gray when it was embedded in a Mondrian with a truncated reflectance range and viewed under very low illumination.

There are a number of methodological differences between our study and theirs that may account for the discrepancy in our findings. Importantly, their subjects made their matches by walking, with eyes open, to a Munsell chart located in a normally illuminated adjacent room. This may have allowed the visual system to integrate (possibly over time) all the spatial reflectance edges lying between the Munsell chart and their Mondrian stimulus.

Our lab is also currently conducting a set of studies to systematically map the behavior of the highest luminance in Mondrian patterns as a function of illumination level. These studies use subjects who memorized the Munsell scale and are able to report lightness without the uncontrolled factors allowed by moving into a different room. Consistent with the result we report here, we find that the lightness of the highest luminance surface (reflectance 90%) is quite stable across an illumination range as large as 6 million-to-one and never appears darker than Munsell 8.3. In addition, separate pilot work suggests that a highest luminance surface (reflectance ~12%), embedded in a Mondrian with a truncated reflectance range viewed within a chamber painted black, behaves similarly, even when the matches are made from immediate memory. Close replications of the study by Anderson et al. (2014), currently ongoing in our lab, will reveal the key factors responsible for the difference in our findings.

Area effect on lightness is strongest when a single dark surface covers most of the visual field

Our experiments provide further support for the area effect on lightness (Gilchrist & Radonjić, 2009). In Experiment 2, we replicated the results of our previous study that established the area effect on dark sector lightness using a subset of the same stimulus set and show that this effect is independent of the overall illumination (luminance) variation. In Experiment 3, we replicated the area effect using a new set of bipartite domes that had different light sector reflectances and different reflectance ranges.

In both experiments, increasing the area of the dark sector relative to the light one caused the dark sector to lighten but had no effect on the light sector. Further, the effect of area on dark sector lightness was larger when the dark sector covered more than half of the visual field.

Importantly, the results of Experiment 3 also show that having a single dark sector fill most of the observer's visual field is a critical condition for the area effect in simple images. When the dark sector is split into four smaller sectors that cover an equal cumulative area, the increase in area of these individual sectors does not have a substantial effect on their lightness. By the same token, when a dark region covers more than half of the observer's visual field, splitting it into smaller sectors causes a significant decrease in its lightness, although its cumulative area remains the same.

In a recent study, Boyaci et al. (2014) extensively studied the area effect on lightness using simulated stimuli (a sectored-disk configuration similar to ours) presented against a low-luminance background on a computer display in a darkened lab. The observers matched sector lightness by adjusting a matching square patch presented at the lower end of the display against a random noise background. Similarly to us, Boyaci et al. addressed the question of whether splitting a single dark sector into multiple sectors equal in cumulative area modulates the area effect on lightness.

There are two main differences between their findings and ours. First, in their stimulus configuration, the area of the dark sector had an effect on lightness even when the dark sector covered less than half of the framework (stimulus and its background). In most cases, however, the relationship between dark sector area and lightness was best captured by a quadratic function that had a shallower slope when the area of the dark region was smaller than that of the lighter and a steeper slope when it was larger. This is consistent with some of our findings discussed earlier. Second, although the effect of area was significantly reduced when the darker region was split into smaller sectors, Boyaci et al. still found that lightness of the dark sector in the multisectored stimuli increased with the increase in individual sector area.

When considering these different findings, it is important to keep in mind the stimulus differences between the two studies. Our study used real, not simulated, surfaces and illuminants, and the stimulus filled the observers' entire visual field. In contrast, the stimuli of Boyaci et al. were simulated, and the display included separate sections for the stimulus and for the matching patch and was presented in the larger laboratory context. Although the stimuli Boyaci et al. used were still fairly simple, we qualify them as complex images as they consist of more than one framework; hence, we consider their study to be not a simple replication of ours but rather a test of applicability of the area effect in more complex stimuli.

Overall, the findings of Boyaci et al. suggest that the area effect we found in simple stimulus conditions does generalize to more complex stimuli. The exact functional form of the effect may depend on the stimulus context, and further research is needed to establish which stimulus characteristics modulate the effect.

Simple images and the applicability assumption

As noted at the outset, our stimuli represent the simplest conditions that support the perception of a surface. This raises the question of whether our findings apply only to very special conditions that occur in the real world rarely, if at all. If so, our results would have only minimal importance, as the main goal is to understand how surface lightness is perceived under the complex conditions typical of natural viewing.

Although we do not believe that our results can be directly applied to more complex images, we nevertheless believe that there is a systematic relationship between the laws of lightness computation in simple images and those that apply to more complex images. Applicability of the single-sector area effect in more complex images is a good example: One can find about a dozen experiments in the lightness literature that used stimuli that qualify as complex images to probe lightness (and/or brightness) as a function of the relative area of the lighter and darker regions, and their findings are consistent with the area effects we report (Wallach, 1948; Diamond, 1955; Heinemann, 1955, 1972; Newson, 1958; Stewart, 1959; Burgh & Grindley, 1962; Kozaki, 1963; Torii & Uemura, 1965; Stevens, 1967; Coren, 1969; Yund & Armington, 1975). That is, strong effects of area on lightness occur only when a darker region covers more than half of the visual field for a simple image or more than half of a framework embedded in a complex image. When this condition is not satisfied, area has little or no effect on lightness.

It is important to note, however, that although the stimuli used in these studies were complex relative to our dome stimuli, the majority of these were still relatively simple and do not capture well the complexity of images that is typical in natural viewing. Therefore, one possible direction of future research is to explore whether the single-sector area rule still holds as stimuli become progressively more complex and naturalistic.

Another open question for further research concerns the mechanisms underlying the area effect. Indeed, our finding that the effect of area on lightness is diminished when the number of dome sectors is increased while the cumulative dark/light area remains the same calls into question whether the phenomenon we describe as the area effect is really caused by the sector area or whether other stimulus characteristics mediate the effect.

For example, darkening of the dark sector in the 270° multisectored dome relative to the bisectored one could be accounted for by a low-level model sensitive to the total length of the borders between the dark and light sectors or a distance-dependent edge integration model sensitive to the relative distance between the light and dark regions (e.g., Rudd, 2013). Such models would also predict darkening of the dark sector outside of the area zone (in the multisectored 90° dome), which is not what we find (but see Boyaci et al., 2014). The explanation of the area effect in terms of low-level mechanisms alone is further contested by the work of Boyaci et al., who show that varying the figure-ground organization of their multisectored stimuli can modify the area effect on lightness, even though the size of the dark and light sectors and their borders remain the same. Further research is therefore required to achieve a better understanding of the mechanisms underlying the area effect.

Keywords: lightness perception, anchoring, highest luminance rule, area rule

Acknowledgments

This work was supported by a National Science Foundation grant (BCS-1230793) and a National Institutes of Health grant (1R25GM096161-01) to Alan L. Gilchrist. The authors would like to thank Huseyin Boyaci, Stephen Ivory, and two anonymous reviewers for their valuable comments on an earlier draft, as well as Jennifer Faasse, Amanda Ebokosia, Camilo Marmolejo, and Oscar Escobar for their help in data collection.

Commercial relationships: none.
Corresponding author: Ana Radonjić.
Email: radonjic@sas.upenn.edu.
Address: Department of Psychology, University of Pennsylvania, Philadelphia, PA, USA.

Footnote

[1]Data for the standard condition of Experiment 2 are identical to those obtained in experiment 2 (11°, 180°, 354° domes) of our previously published study on the area effect on lightness (Gilchrist & Radonjić, 2009), which was conducted in parallel with this work.

References

Anderson, B. L., Whitbread, M., & de Silva, C. (2014). Lightness, brightness, and anchoring. *Journal of Vision, 14*(9):7, 1–13, http://www.journalofvision.org/content/14/9/7, doi:10.1167/14.9.7. [PubMed] [Article]

Annan, V., & Gilchrist, A. (2004). Lightness depends on immediately prior experience. *Perception & Psychophysics*, *66*, 943–952.

Boyaci, H., Kobal, M., & Subasi, E. (2014). Effect of contiguity and figure-ground organization on the area rule of lightness. *Journal of Vision, 14*(13):26, 1–11, http://www.journalofvision.org/content/14/13/26, doi:10.1167/14.13.26. [Article]

Buchsbaum, G. (1980). A spatial processor model for object colour perception. *Journal of the Franklin Institute*, *310*, 1–26.

Burgh, P., & Grindley, G. C. (1962). Size of test patch and simultaneous contrast. *Quarterly Journal of Experimental Psychology*, *14*, 89–93.

Cataliotti, J., & Bonato, F. (2003). Spatial and temporal lightness anchoring. *Visual Cognition*, *10*, 621–635.

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

Diamond, A. L. (1955). Foveal simultaneous contrast as a function of inducing-field area. *Journal of Experimental Psychology*, *50*, 144–152.

Efron, B., & Tibshirani, R. J. (1993). *An introduction to the bootstrap*. New York: Chapman and Hall/CRC.

Gilchrist, A., Kossyfidis, C., Bonato, F., Agostini, T., Cataliotti, J., Li, X., . . . Economou, E. (1999). An anchoring theory of lightness perception. *Psychological Review*, *106*, 795–834.

Gilchrist, A. L. (2006). *Seeing black and white*. Oxford, UK: Oxford University Press.

Gilchrist, A. L., & Radonjić, A. (2009). Anchoring of lightness values by relative luminance and relative area. *Journal of Vision, 9*(9):13, 1–10, http://www.journalofvision.org/content/9/9/13, doi:10.1167/9.9.13. [PubMed] [Article]

Heinemann, E. (1972). Simultaneous brightness induction. In D. Jameson & L. Hurvich (Eds.), *Handbook of sensory physiology: Visual psychophysics* (Vol. 7/4, pp. 146–169). Berlin: Springer.

Heinemann, E. G. (1955). Simultaneous brightness induction as a function of inducing- and test-field luminances. *Journal of Experimental Psychology*, *50*, 89–96.

Helson, H. (1964). *Adaptation-level theory: An experimental and systematic approach to behavior*. New York: Harper & Row.

Horn, B. K. P. (1986). *Robot vision*. Cambridge, MA: MIT Press.

Kardos, L. (1934). Ding und Schatten: Eine experimentelle Untersuchung über die Grundlagen des Fabensehens. *Zeitschrift für Psychologie*, *23*, 1–184.

Kozaki, A. (1963). A further study on the relationship between brightness constancy and contrast. *Japanese Psychological Research*, *5*, 129–136.

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

Li, X., & Gilchrist, A. (1999). Relative area and relative luminance combine to anchor surface lightness values. *Perception & Psychophysics*, *61*, 771–785.

Marr, D. (1982). *Vision*. San Francisco: W. H. Freeman.

Metzger, W. (1930). Optische Untersuchungen am Ganzfeld. *Psychologische Forschung*, *13*, 6–29.

Newson, L. J. (1958). Some principles governing changes in the apparent lightness of test surfaces isolated from their normal backgrounds. *Quarterly Journal of Experimental Psychology*, *10*, 82–95.

Radonjić, A., & Gilchrist, A. L. (2013). Depth effect on lightness revisited: The role of articulation, proximity and fields of illumination. *i-Perception*, *4*, 437–455.

Rudd, M. E. (2013). Edge integration in achromatic color perception and the lightness-darkness asymmetry. *Journal of Vision, 13*(14):18, 1–30, http://www.journalofvision.org/content/13/14/18, doi:10.1167/13.14.18. [PubMed] [Article]

Stevens, J. (1967). Brightness inhibition re size of surround. *Perception & Psychophysics*, *2*, 189–192.

Stewart, E. C. (1959). The Gelb effect. *Journal of Experimental Psychology*, *57*, 235–242.

Torii, S., & Uemura, Y. (1965). Effects of inducing luminance and area upon the apparent brightness of test field. *Japanese Psychological Research*, *7*, 86–100.

Wallach, H. (1948). Brightness constancy and the nature of achromatic colors. *Journal of Experimental Psychology*, *38*, 310–324.

Yund, W. E., & Armington, J. C. (1975). Color and brightness contrast effects as a function of spatial variables. *Vision Research*, *15*, 917–929.

Appendix A: Observers and outliers

Table A1 provides an overview of the total number of observers included in the analysis and the number of excluded outliers for each experiment and condition.

Illumination	Lowest	Second lowest	Medium	Standard	High
Experiment 1					
180° dome	21 (0)	19 (2)	20 (0)	19 (2)	
Experiment 2					
11° dome	25 (1)	20 (2)	21 (1)	20 (0)	20 (1)
180° dome	19 (1)	21 (1)	19 (1)	20 (0)	22 (1)
354° dome	26 (1)	18 (2)	19 (1)	20 (1)	21 (0)
Experiment 3					
Dark sector area	22°	90°	270°	338°	
Bipartite	20 (1)	20 (0)	21 (1)	20 (0)	
Multipartite		18 (2)	21 (0)		

Table A1. Number of observers per condition. For each experimental condition, the table shows the total number of included observers with the number of outliers in parentheses.

Appendix B: Lightness matches: Means and standard deviations

Table A2 provides the means and standard deviations of lightness matches for each dome sector in all experiments and conditions in both Munsell and log % reflectance values.

Dome	Sector	Illumination level	Lowest	Low	Medium	Standard	High
Experiment 1							
180°	Light	Log % ref	1.84 (0.07)	1.85 (0.08)	1.87 (0.06)	1.88 (0.05)	
		Munsell	8.55 (0.52)	8.61 (0.64)	8.82 (0.47)	8.87 (0.44)	
	Dark	Log % ref	1.57 (0.13)	1.58 (0.14)	1.61 (0.11)	1.68 (0.08)	
		Munsell	6.64 (0.85)	6.66 (0.87)	6.90 (0.72)	7.37 (0.55)	
Experiment 2							
11°	Light	Log % ref	1.86 (0.10)	1.89 (0.05)	1.92 (0.04)	1.89 (0.06)	1.92 (0.05)
		Munsell	8.74 (0.81)	8.93 (0.41)	9.17 (0.33)	8.97 (0.47)	9.22 (0.38)
	Dark	Log % ref	1.14 (0.16)	1.17 (0.22)	1.27 (0.20)	1.24 (0.28)	1.30 (0.23)
		Munsell	4.32 (0.73)	4.50 (1.04)	4.98 (1.04)	4.88 (1.35)	5.15 (1.10)
180°	Light	Log % ref	1.89 (0.06)	1.92 (0.04)	1.92 (0.04)	1.91 (0.05)	1.92 (0.04)
		Munsell	8.95 (0.52)	9.17 (0.33)	9.18 (0.30)	9.10 (0.38)	9.25 (0.34)
	Dark	Log % ref	1.24 (0.18)	1.40 (0.16)	1.38 (0.16)	1.37 (0.14)	1.42 (0.20)
		Munsell	4.79 (0.87)	5.60 (0.89)	5.50 (0.87)	5.45 (0.79)	5.75 (1.10)
354°	Light	Log % ref	1.86 (0.07)	1.91 (0.05)	1.90 (0.04)	1.93 (0.03)	1.91 (0.04)
		Munsell	8.69 (0.55)	9.14 (0.45)	9.08 (0.34)	9.28 (0.26)	9.12 (0.31)
	Dark	Log % ref	1.43 (0.23)	1.57 (0.19)	1.55 (0.26)	1.72 (0.09)	1.64 (0.11)
		Munsell	5.88 (1.37)	6.64 (1.19)	6.63 (1.50)	7.62 (0.63)	7.10 (0.77)
Dome	**Sector**	**Area**	**22**	**90**	**270**	**338**	
Experiment 3							
Bisectored	Light	Log % ref	1.88 (0.02)	1.91 (0.01)	1.90 (0.01)	1.92 (0.01)	
		Munsell	8.88 (0.16)	9.10 (0.11)	9.02 (0.11)	9.18 (0.08)	
	Dark	Log % ref	1.00 (0.08)	1.00 (0.05)	1.54 (0.04)	1.69 (0.03)	
		Munsell	3.85 (0.34)	3.77 (0.21)	6.50 (0.27)	7.47 (0.20)	
Multisectored	Light	Log % ref		1.89 (0.02)	1.89 (0.01)		
		Munsell		8.97 (0.12)	8.98 (0.07)		
	Dark	Log % ref		1.09 (0.04)	1.22 (0.05)		
		Munsell		4.11 (0.17)	4.71 (0.24)		

Table A2. Means and standard deviations (in parentheses) of lightness matches for each dome sector are shown for each experiment and condition in both log % reflectance and Munsell values.