Context affects lightness at the level of surfaces

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Visual perception of object attributes such as surface lightness is crucial for successful interaction with the environment. How the visual system assigns lightness to image regions is not yet understood. It has been shown that the context in which a surface is embedded influences its perceived lightness, but whether that influence involves predominantly low-, mid-, or high-level visual mechanisms has not been resolved. To answer this question, we measured whether perceptual attributes of target image regions affected their perceived lightness when they were placed in different contexts. We varied the sharpness of the edge while keeping total target flux fixed. Targets with a sharp edge were consistent with the perceptual interpretation of a surface, and in that case, observers perceived significant brightening or darkening of the target. Targets with blurred edges rather appeared to be spotlights instead of surfaces; for targets with blurred edges, there was much less of a contextual effect on target lightness. The results indicate that the effect of context on the lightness of an image region is not fixed but is strongly affected by image manipulations that modify the perceptual attributes of the target, implying that a mid-level scene interpretation affects lightness perception.

Introduction

The goal of this work was to understand the nature of the computations involved in assigning perceived lightness to retinal image regions. It is well known that the lightness of an image region is influenced by the luminances of the regions that *surround* it. Surround effects have been demonstrated in simple two-dimensional stimulus arrangements, such as simultaneous brightness contrast (e.g., Wallach, 1948) or White's effect (White, 1979), as well as in complex images in which compelling effects of depth on lightness were found (e.g., Gilchrist, 1980; Mach, 1886; Radonjic & Gilchrist, 2013; Radonjic, Todorovic, & Gilchrist, 2010). Accordingly, different mechanisms have been proposed to account for the influence of the surround, ranging from local, presumably retinal or early cortical, mechanisms that respond to the physical contrast between an object and its background (Blakeslee & McCourt, 2004; Rudd, 2010; Shapley & Reid, 1985; Wallach, 1948) to mechanisms that involve the objects' geometry and the depth structure and illumination in a scene (Adelson, 1993; Anderson & Winawer, 2005; Bloj, Kersten, & Hurlbert, 1999; Boyaci, Doerschner, Snyder, & Maloney, 2006; Gilchrist, 1977; Knill & Kersten, 1991; Purves, Shimpi, & Lotto, 1999).

Variations in image intensity (i.e., in luminance) can lead to different perceptual interpretations: They can either be attributed to differences in the lightness of a surface (i.e., its paint color) or to differences in brightness (i.e., its illuminance). Previous studies have demonstrated that observers show different matching behavior depending on whether they are instructed to judge lightness or brightness (e.g., Arend & Spehar,

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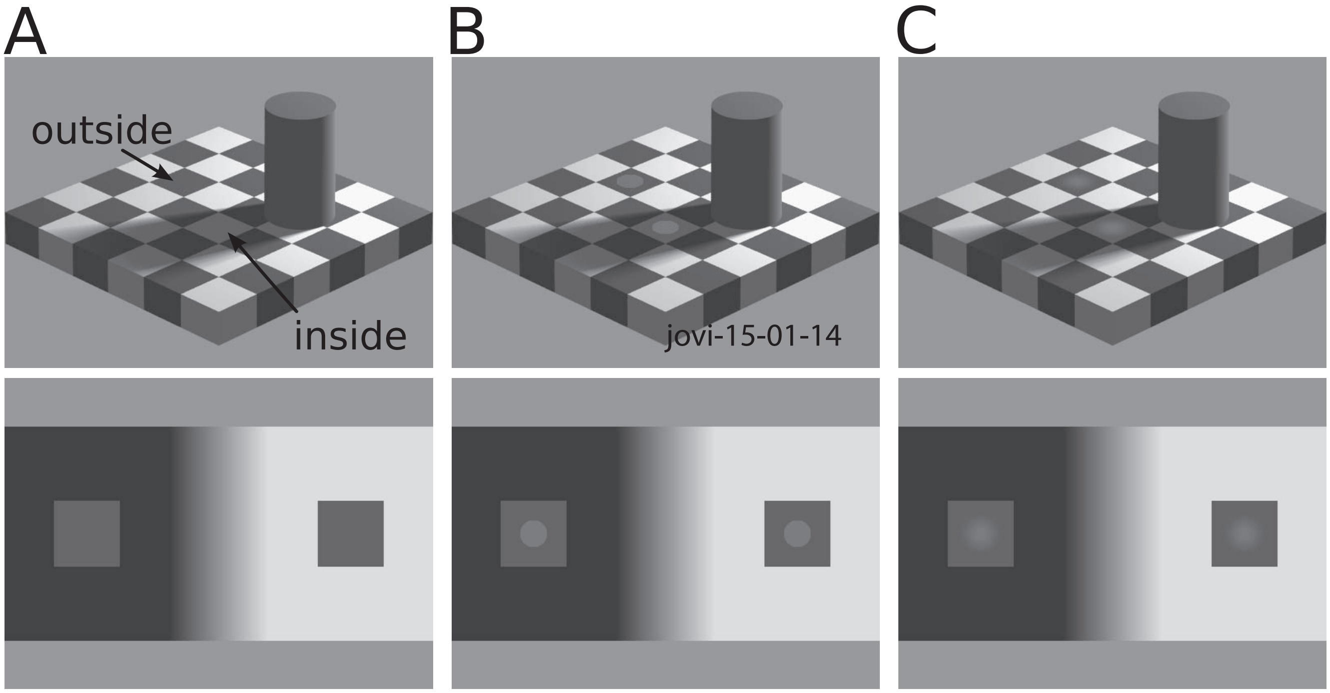

Figure 1. Experimental stimuli. (A) Customized version of the AC indicating equiluminant checks inside and outside the shadow; below: SR stimulus. Check and square luminances were identical and 58 cd/m^2. Surround luminances were also chosen to be comparable and were on average 171 cd/m^2 for light surrounds and 28 cd/m^2 for dark surrounds. (B) AC and SR stimulus with equiluminant ellipses placed on test checks and surround square, respectively. (C) Analogous to (B) but with blurred ellipses. The ellipses with sharp boundaries look like proper surfaces whereas the blurred ellipses are more consistent with the cone of a spotlight. The "lightness" difference between ellipses located on increments versus decrements seems to be attenuated for the blurred compared to the proper ellipses.

1993a, 1993b). It will become evident below that with more natural stimuli and in the absence of specific instructions, it is still an open question under which conditions observers will be judging (and perceiving) lightness or brightness. Unless further specified, we use the term lightness to refer to perceived intensity variations along the black-and-white continuum.

In the present experiment, we tested whether a target might be perceived as different in lightness in the absence of changes in the surround but due to differences in the perceptual interpretation of the target itself. We used a customized version of the Adelson checkershadow (AC) demonstration as stimulus (Figure 1A, upper row). The critical checks in the checkershadow demonstration are those labeled "inside" and "outside" in Figure 1A. These checks are identical in luminance but look different in lightness as the check *inside* the shadow appears to be one of the white checks and the check *outside* the shadow appears to be one of the black checks. However, the checks do not only differ with respect to their location inside or outside the shadow, but they also differ with respect to their local surround luminances. The difference in apparent lightness between the two equiluminant checks could thus be due to a lower-level computation based on the contrast effect of the local surround, or alternatively, it could be the result of a higher-level computation that compensates for illumination differences in the shadowed or unshadowed regions of the checkerboard. A third possibility is that the lightness difference results from a combination of the contrast computation and the illumination computation in an as yet to be determined manner. Kingdom (2011) concluded, in a recent review of the field, that because of the difficulty in eliminating possible explanations, there has been "unrelenting controversy" about deciding between alternative explanations for lightness perception.

Instead of comparing the perceived lightness of the critical checks, about which there has been "unrelenting controversy," we asked observers to compare the lightness of elliptical targets that were placed on top of each of the critical checks as in Figure 1B, upper row (Gilchrist, 2006; Gilchrist & Radonjic, 2010; Hillis & Brainard, 2007; Maertens & Wichmann, 2013). The targets are not only equal in luminance, but they are also equal in local luminance contrast because the critical checks are equiluminant as well. As is evident from the upper row image in Figure 1B, the ellipses placed on white and black checks appear different from each other in lightness. Note that the lightness difference of the ellipses in the upper row of Figure 1B is an instance of a phenomenon called assimilation (Gilchrist, 2006; Jameson & Hurvich, 1975; Shapley & Reid, 1985). Assimilation is the opposite of contrast: Targets on a black background tend to appear darker, and targets on a white background tend to appear lighter. In the present case, the check inside the shadow looks lighter than the check outside the shadow (Figure 1A, upper row). Because the former is surrounded mainly by dark and the latter mainly by light checks, that effect could be described in part as a contrast effect because the lightnesses of the two equiluminant checks are moved away from their respective surrounding. For the two equiluminant ellipses, the situation is different (Figure 1B, upper row). The ellipse located on the (lighter) check inside the shadow looks lighter than the ellipse located on the (darker) check outside the shadow: Each ellipse's lightness change shifts toward the appearance of its local surround.

The main question of this paper is whether changing image features that might be accompanied by a change in the perceptual interpretation of the target ellipses would affect the perceived lightness of the targets. We compared the perceived lightness of the ellipses with ellipses that had blurred borders (Figure 1C, upper row). Blurred ellipses have previously been used in studies that addressed the relationship between the discriminability and appearance of surface lightness (Hillis & Brainard, 2007; Maertens & Wichmann, 2013). In these studies, the blurring of the boundaries was introduced to avoid ceiling effects due to the high human contrast sensitivity, but there is also a perceptual consequence of blurring the boundary: The blurring made the blurred ellipses more consistent with the cone of a spotlight than with a solid surface (Figure 1C, upper row). If that perceptual impression is consistent with how the visual system interprets the blurred ellipses, then one might expect differences in how the lightnesses of ellipses and blurred ellipses are affected by assimilation from their surroundings. This is what was observed.

In order to test for the importance of realism for the lightness effects observed with the checkershadow stimulus, we also presented ellipses and blurred ellipses in a simultaneous lightness contrast type of display. We used a version of the stimulus (Figure 1A, lower row) in which the target regions are embedded in two larger regions of different luminance that are linked by a uniform luminance gradient (Shapley & Reid, 1985). This stimulus is less realistic than the AC image. It has no cues for depth and is photometrically much simpler (less articulated) than the checkershadow. But it does have the same luminance relationships of the target and surround regions as the AC (see Figure 1, lower row, and Methods). We report below that a similar difference in lightnesses between sharp-edge and blurred ellipses was observed with the less realistic display (Figure 1B, lower row), but the lightness differences between elliptical targets were smaller.

Methods

Observers

Eight observers took part in each of the experiments. Three of them participated in both experiments; one was one of the authors (MM). One observer was excluded from the analysis of the mutual matching in the main experiment because he evidently performed a luminance-matching strategy that was profoundly different from how he verbally reported to have perceived the stimuli. All participants except the author were naive to the purpose of the experiment. Five observers in the first and three in the second experiment were female. Observers' ages ranged from 20 to 34 years. All observers had normal or corrected-to-normal visual ability. All naive observers participated voluntarily and were reimbursed for their attendance.

Stimuli and apparatus

Stimuli were presented on a linearized 21-in. Siemens SMM 21 106 LS monitor (400 × 300 mm, 1024 × 766 pixel, 130 Hz) controlled by a Cambridge Research Systems 10-bit graphics card. In the present experiments, we used a look-up table of 256 linearly spaced luminance values spanning a range between 28 and 196 cd/m^2.

The AC was rendered using Povray software (Persistence of Vision Pty. Ltd., 2004). Ambient light was simulated by adding a small amount of white light to each texture whether or not the defined light source was actually shining on that texture. The light source was an area light that consisted of a regular grid of 12 by 12 individual light sources. The resulting image was converted to a gray scale matrix using the imaging library in Python (PIL). The checkerboard subtended 13.5° visual angle in the horizontal and 7.2° in the vertical direction. Individual checks had an edge length of about 1.1°. The critical checks inside and outside the shadow in the AC had a luminance of 58.2 cd/m^2. The luminances of the white checks adjacent to the check outside the shadow were 166, 179, 176, and 164 cd/m^2 (starting from upper left, clockwise), and the luminances of the dark checks adjacent to the check inside the shadow were 30, 28, 28, and 27 cd/m^2.

The Shapley and Reid (SR) stimulus was created as a two-dimensional gray scale matrix directly in Python. It had the same spatial dimensions as the AC. The SR stimulus was composed of two plateau regions, dark

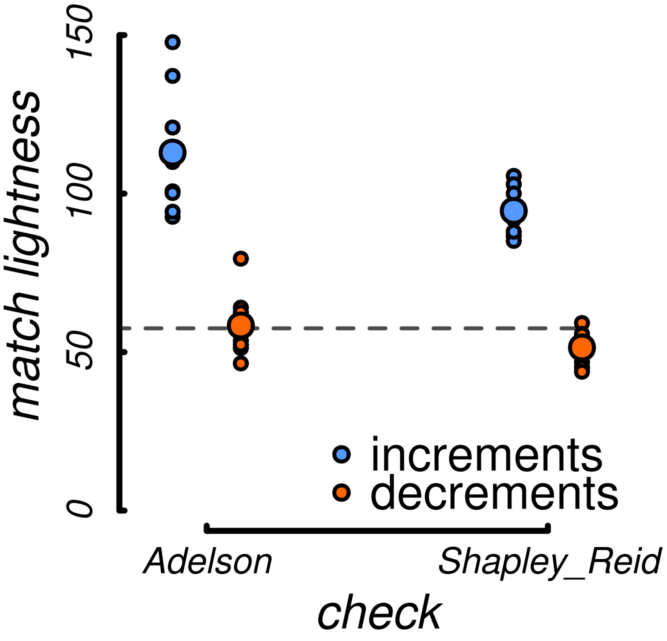

Figure 2. Lightness as a function of context. Perceived lightness is plotted as a function of stimulus type (x-axis) and the type of target (symbols). Throughout the manuscript, lightness matches are expressed in units of luminance, cd/m^2, of the adjustable reference region. The external reference was a square region presented on a small checkerboard background (see Figure 6B, inset). Small symbols represent data of individual observers and large symbols the means across observers ($n = 8$). The dashed line indicates the actual luminance of the target regions.

and light, which were 5.2° wide and which were connected by a luminance gradient. The luminance values for the plateau regions were chosen so as to be comparable to the luminances of the four checks that were directly adjacent to the two critical checks in the AC. Within the adjacent four surround checks, we considered only the luminance values along the boundaries with the target checks. The luminance of the light plateau was 171 cd/m^2, and that of the dark plateau was 27 cd/m^2. The surround squares were 2.7° wide, and their luminances were both identical to those of the critical checks in the checkerboard 58.2 cd/m^2. Accordingly, the Rayleigh contrast of the decremental checks or squares was -0.49, and that of the incremental checks or squares was 0.36, and it was identical in both types of stimuli (the Rayleigh contrast is the luminance difference between target and surround divided by their sum). The luminance of the background was 106 cd/m^2.

Two types of targets were used for the matching: ellipses or circles with proper borders and those with blurred borders. Targets with proper borders were 0.72° visual angle wide (ellipses' height was half their width). Blurred targets were 0.98° visual angle wide in order to equalize the volume under the increment relative to targets with sharp boundaries. Blurred ellipses were defined as $[1 + cos(D \times \pi)]/2$, whereby D was defined as $D = min(1, \sqrt{x^2 + y^2})$, and within D, a central region of plateau radius was set to zero to create a plateau at the peak of the ellipse. Targets were centered on the respective checks or surround squares. Each target was presented at seven different intensities, which increased in steps of about 6.5 cd/m^2 starting from the luminance of the checks or squares.

When observers performed the matching with an external reference, this external reference was a square (1.3°) that was presented on a local coplanar checkerboard (3.6° × 3.6°, see Figure 6A, icon above right panel). The checkerboard consisted of eight by eight small checks with intensities that were randomly drawn from 20 equally spaced luminance values between the minimum and maximum of the look-up table. The resulting mean luminance of the checkerboard surrounding the reference was 112 cd/m^2 and hence close to the background luminance. All stimuli were created prior to the experiments and loaded later for presentation. Observers were seated 100 cm away from the screen in an experimental cabin that was dark except for the light emitted by the monitor.

Procedure

The experiment consisted of two parts: In the first part, we measured the effect of the context on the appearance of the two checks inside and outside the shadow in the AC and of the test squares on the dark or light plateau in the SR stimulus (see Figure 2). Observers adjusted the luminance of an external reference until it looked like one of these four targets. Five matches were performed for each target.

In the second part of the experiment, we measured the appearance of ellipses or blurred ellipses in the AC and SR stimuli (see Figures 3 and 5A). Critically, the difference from the first part of the experiment is that the local context was identical for all targets. For the measurements on the AC, we presented a series of ellipses (or blurred ellipses) of varying luminances.

The ellipses were always increments; they were presented at seven different, equally spaced incremental luminances (from 64.7 up to 103.7 cd/m^2). Observers performed a mutual matching task: A test ellipse was presented, say on a decrement check, and the observer adjusted the luminance of a similarly shaped ellipse on the increment check to match the apparent lightness of the presented ellipse (or blurred ellipse). And vice versa, ellipses presented on increment checks were matched by adjustment of ellipses on the decrement check. Observers were instructed to adjust the intensity of the match so that it looked most similar to the target. Five repeats were performed for each combination of target

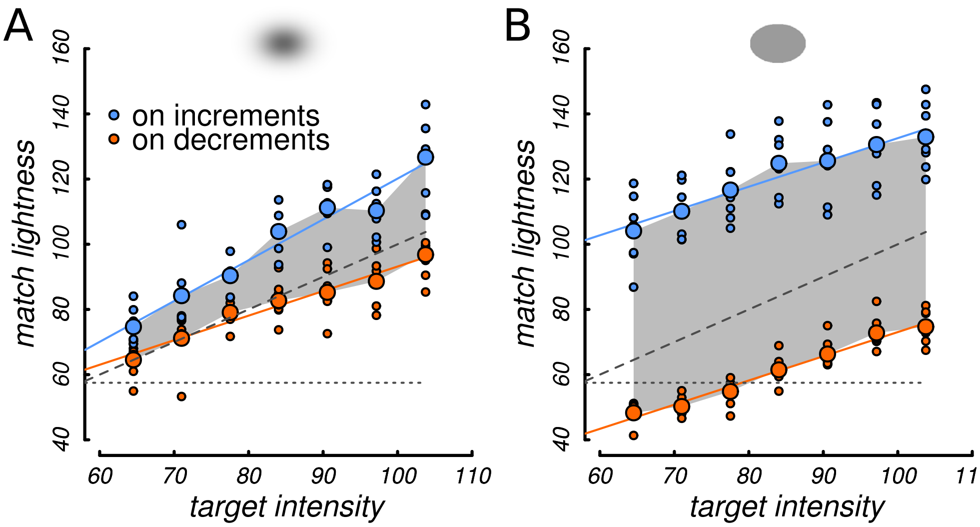

Figure 3. Lightness matches in the AC in the mutual matching task. Luminance matches (in cd/m^2) are plotted as a function of target intensity (x-axis). Targets were located on increments (in the shadow) or on decrements (outside the shadow). Either blurred or proper ellipses (icons on the top of the panels) were matched to each other, that is, a target ellipse located on an increment (blue) had to be matched with a test ellipse located on a decrement or vice versa. Small points are individual data, and larger points depict the average. The shaded area depicts the area between the mean data from targets on increments and decrements. The dashed line indicates luminance equality between target and match, and the dotted line indicates the check luminance.

intensity, target type, stimulus type, and target position. The target intensity and target type (sharp-edge vs. blurred) were randomized across trials but target position (inside vs. outside shadow or on dark vs. light plateau) was blocked. In a separate block of trials, similar measurements were made on the SR stimulus with sharp-edge versus blurred circular stimuli.

We also performed a control experiment in which observers judged the apparent lightness of the elliptical (or circular) targets by means of an external matching task in addition to the mutual matching task. The purpose of this experiment was to test whether the lightness matches for the elliptical or circular targets that were observed with the mutual matching task

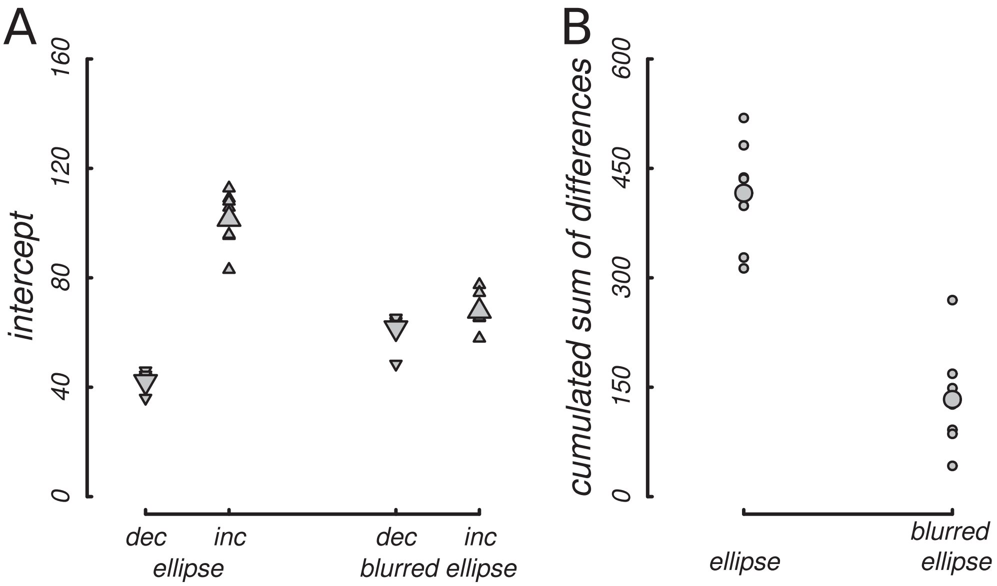

Figure 4. Intercepts and cumulative sums of differences for lightness matches on increments and decrements in the AC stimulus. (A) Linear regressions were fit to the matching data in Figure 3 separately for targets on increments (inc, Δ) and on decrements (dec, ∇). Intercepts were determined at zero incremental luminance and are shown separately for increments and decrements and for ellipses and blurred ellipses. (B) Cumulative sums of differences between matches for targets on increments and decrements are plotted as a function of target type. The cumulated sum of differences corresponds to the gray-shaded area in Figure 3.

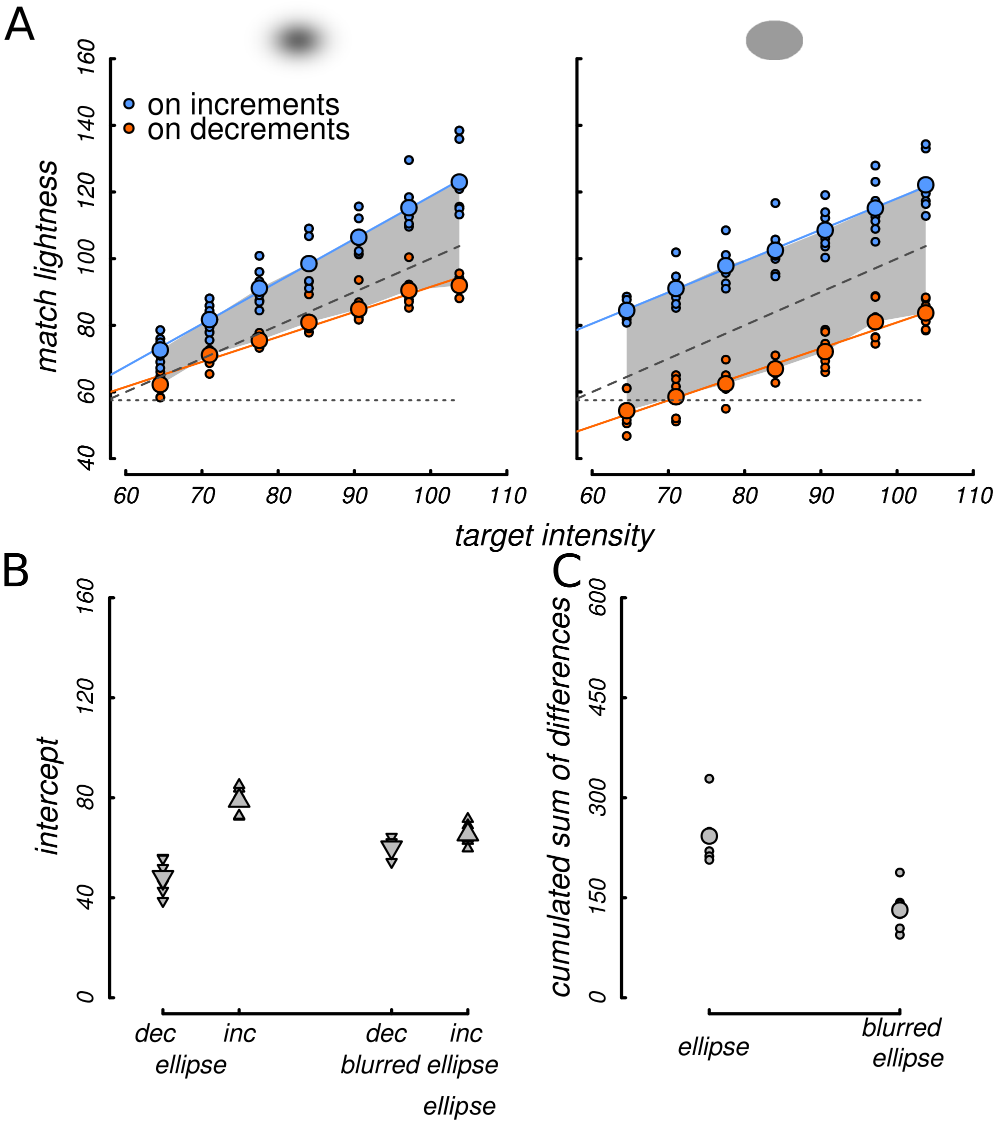

Figure 5. Lightness matches, intercepts, and cumulative sums of differences of the lightness matches in the SR stimulus. The layout in (A) corresponds to the layout in Figure 3, and the layout in (B) and (C) correspond to the layout in Figure 4.

would be replicable with an external matching task. This was necessary to allow a comparison of the effect magnitudes between the first and the second parts of the experiment. The mutual matching was identical to the one described above for the second part of the experiment. For the external matching, a single ellipse (or circle) was presented in a given trial, and observers adjusted the external reference square so as to match the lightness of the target. This was identical to the external matching in the first part of the experiment. Only targets with sharp boundaries were tested because it was impossible to accomplish a satisfying match between blurred targets and external matches. The starting luminance values of the external reference or of the adjustable ellipses were assigned randomly in each trial. Observers could adjust the luminance of the reference using a five-button response, with which they could increase or decrease the luminance at two different step widths (0.65 and 6.6 cd/m^2). The fifth button triggered the next trial. The stimuli lasted until observers were satisfied with their matches.

Results

Lightness differences in different contexts

The first measurements were of the lightness difference between the dark and light squares of equal luminance ∼58 cd/m^2 in the SR stimulus and the equiluminant checks labeled "outside" and "inside" in the AC (Figure 1A). To make this measurement, observers were instructed to adjust the luminance of an

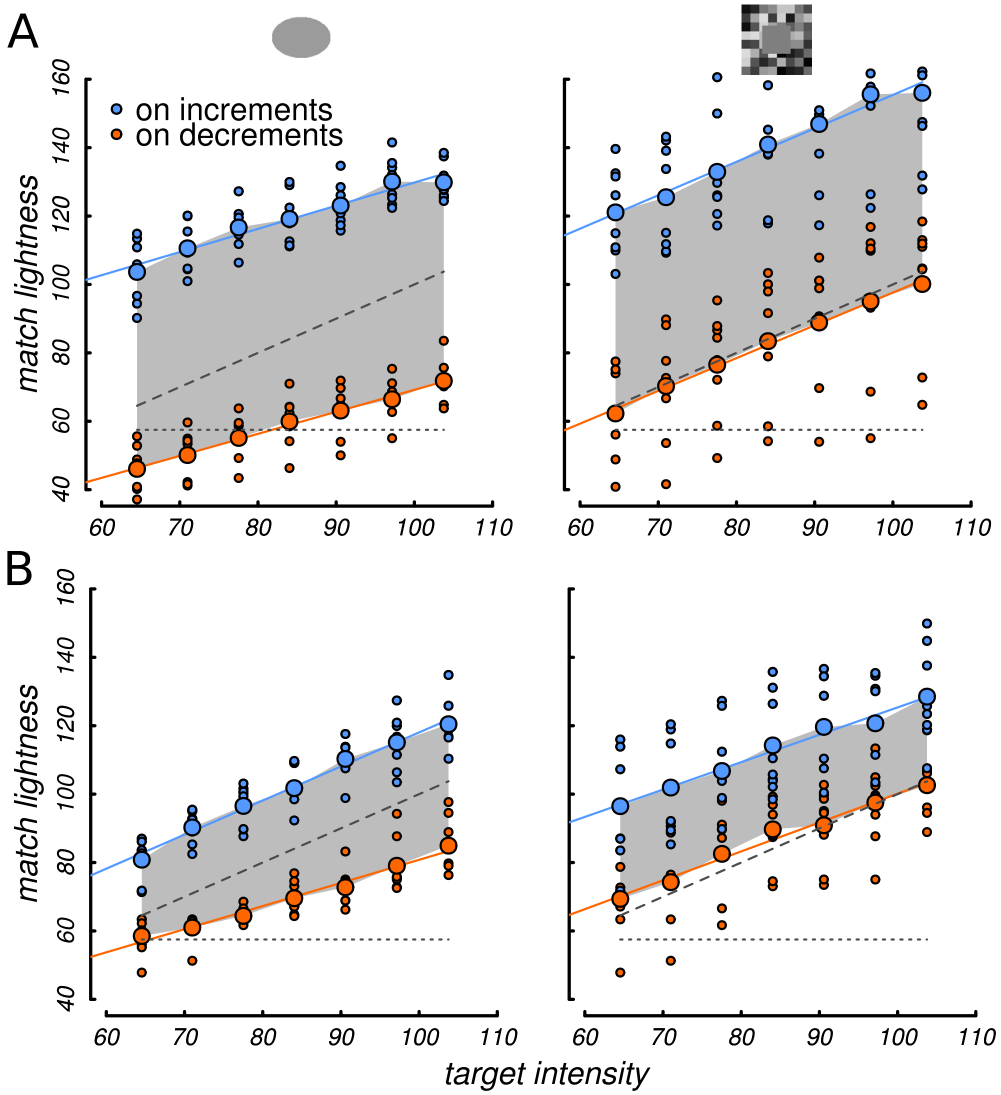

Figure 6. Lightness matches in the control experiment comparing mutual and external matching. Luminance matches (in cd/m^2) are plotted as a function of target intensity (x-axis). Targets were located on increments (in the shadow) or on decrements (outside the shadow). (A) AC; (B) SR stimulus; left column: mutual matching of ellipses analogous to data presented in Figures 3 and 5; right column: an external reference (icon above the panel) was adjusted so as to match target ellipses of different intensities on incremental or decremental checks. The mean background of the external reference was 112 cd/m^2. Small points are individual data, and larger points depict the average. The variability between and within observers was higher for the external than for the mutual matching, an effect that is often observed for asymmetric matches, i.e., matches between different contexts. The shaded area depicts the area between the mean data from targets on increments and decrements. The dashed line indicates luminance equality between target and match, and the dotted line indicates the check luminance.

external reference region so that it would match the perceived lightness of the test checks (squares). The results are depicted in Figure 2. To test for the statistical significance of the observed differences, we computed a two-by-two repeated-measures ANOVA with the factors stimulus type (AC vs. SR) and target type (dark, decremental vs. light, incremental target). A main effect was observed for the target type, $F(1, 7) = 76.31$, $p < 0.001$. Incremental target regions were perceived as markedly lighter than decremental ones (104 vs. 55 cd/m^2, respectively).

However, there was no significant difference between stimulus types (AC and SR) and no significant interaction between stimulus and target types. Although the interaction effect between the factors stimulus and target type was not significant, we also report the perceived lightness differences between decremental and incremental checks separately for the two stimulus types because the numbers will be important for later comparisons. In the AC, the check "outside the shadow" (decrement) was matched to a square of luminance 58 cd/m^2, and the check "inside the shadow" (increment) was matched to a square of luminance 113 cd/m^2. In the SR stimulus, the decremental square was matched by a square in the reference stimulus of 51 cd/m^2, and the incremental square was matched with 95 cd/m^2. Hence, the mean differences in matching luminances between the equiluminant squares were 55 cd/m^2 in the AC stimulus and 44 cd/m^2 in the SR stimulus.

In Figure 2, the horizontal dashed line is drawn to indicate the luminance of the checks and squares in the AC and SR stimuli. The average matching luminances in the reference stimulus to the decremental check and square were approximately the same as the luminance of the check (and square). But we believe the agreement of the matching luminances to the luminance of the decremental check (and square) was fortuitous and that it was a consequence of the choice of the average luminance of the surround checks in the reference stimulus (see Methods).

Assimilation of ellipses and blurred ellipses

In the second part of the main experiment, we compared the perceived lightness of ellipses and blurred ellipses placed on top of the equiluminant checks that appeared light and dark. To assess the perceived lightness of the elliptical test regions, we asked the observers to perform a mutual matching task. The observers adjusted the luminance of one ellipse to match the perceived lightness of the other. For instance, to gauge the lightness of an ellipse (the target) placed on the lighter (inside-the-shadow) check, the observer adjusted the luminance of the ellipse placed on the darker (outside-the-shadow) check to match the lightness of the target. The targets were presented at seven different intensities (from 64.7 up to 103.7 cd/m^2, see Methods), all of higher luminance than the background check (which was always 58 cd/m^2, see Methods). Results for the AC stimulus are shown in Figure 3. With this paradigm, each pair of points at the same target intensity had the same luminance and the same local luminance contrast with their respective backgrounds, which by design also were of the same luminance. The vertical distance between the points of a given target intensity was a measure of the strength of assimilation. Observers performed the same mutual matching for blurred ellipses, and the results for those experiments are shown also in Figure 3.

As evident from Figure 3, the perceived lightness difference for blurred ellipses was much less (Figure 3A) than for ellipses with sharp edges (Figure 3B). We quantified the difference between sharp and blurred ellipses in two different ways. First, the data for each condition were fit with a straight line, and the intercepts at zero incremental luminance were compared for sharp and blurred ellipses (Figure 4A). In Figures 3 and 5A, the intercepts of the lines with the y-axis correspond to the "zero increment." These intercepts at zero increment are interesting because they provide an independent estimate for the perceived lightness of the checks on which the elliptical targets were placed. A target of zero incremental intensity is equivalent to the check's own intensity, and hence, the intercepts can be compared to the matches obtained in the first part of the main experiment.

A two-by-two repeated-measures ANOVA with the factors target type (proper vs. blurred ellipse) and target location (on increments vs. on decrements) revealed a significant interaction between the two factors, $F(1, 6) = 56.2$, $p < 0.001$. Post hoc t tests showed that the intercepts for the blurred ellipses on the darker (outside) check and on the lighter (inside) check differed only by 6 cd/m^2 (62 vs. 68 cd/m^2). This difference was not significant. For the sharp-edge ellipses, there was a difference of 59 cd/m^2 between the intercepts on light and dark checks (101 vs. 42 cd/m^2). This difference was statistically significant, $t(6) = 16.5$, $p < 0.001$.

A second method of quantification was to compute the cumulative sum of the differences between the matching luminances for the ellipses on the darker and lighter checks (Figure 4B). The cumulative sum is proportional to the shaded gray regions drawn in Figure 3. For the sharp-edge ellipses, the cumulative sum was 416 cd/m^2, and for the blurred ellipses, it was 133 cd/m^2; a paired t test revealed that the difference between these values was significant, $t(6) = 8.6$, $p < 0.001$. Dividing the cumulative sum of the differences by seven, i.e., the number of incremental target luminances, gives the average matching luminance difference between pairs of (equally luminant) ellipses on light and dark checks. For the sharp-edge ellipses, this calculation equals 60 cd/m^2, almost identical to the difference between the intercepts on the light and dark checks, which was 59 cd/m^2. The agreement is consistent with the appearance of the data in Figure 3, in which the sharp-edge ellipse points are well fit with two parallel straight lines. However, for the blurred ellipses, the intercepts do not agree with the cumulative difference averaged over the points: The two values are 6 and 19 cd/m^2, respectively, because for the blurred ellipses the best-fitting lines for the data on the light and dark checks were not parallel.

The effect of blurring the edges of the target ellipse was also evident but smaller on the SR background (Figure 5). A two-by-two repeated-measures ANOVA yielded a significant interaction effect between the factors target type and target location, $F(1, 6) = 63.3$, $p < 0.001$. The difference in intercepts between targets on dark and light squares was 31 cd/m^2 for the sharp-edge ellipses (48 vs. 79 cd/m^2), respectively, $t(6) = 12$, $p <$

0.001, and 5 cd/m^2 for the blurred ellipses (60 vs. 65 cd/m^2), respectively, $t(6) = 2.8$, $p = 0.03$. The cumulative sums in this case were 243 cd/m^2 for the ellipses and 132 cd/m^2 for the blurred ellipses, again significantly different according to a paired *t* test, $t(6) = 9.6$, $p < 0.001$, but a smaller difference than for the AC. Again for SR stimuli the intercepts and average differences between the seven target intensities were in agreement for the sharp-edge ellipses: 31 versus 35 cd/m^2 whereas the blurred-ellipse data revealed a discrepancy between intercepts of 5 cd/m^2 and the average difference between the seven target intensities of 19 cd/m^2 as in the case of AC stimuli. The main result is that the perceived lightness of ellipses depended strongly on the edge profile of the ellipse for both AC and SR stimuli.

We noticed that the slopes for the linear functions relating match to target intensity were different between targets on increments and on decrements for the blurred ellipses. To test that observation, we performed the same two-by-two repeated-measures ANOVA as for the intercepts at zero incremental target intensity. The ANOVA yielded significant main effects and a significant interaction. However, as confirmed by post hoc *t* tests, the main effects were due to the single deviating slope for targets on increments in the blurred-ellipse condition. In the AC stimulus, the slopes were 0.75 and 0.74 for sharp-edge targets on increments and decrements, respectively. For blurred-edge targets, the slopes were 1.25 and 0.75 on increments and decrements, respectively. Significant differences revealed by *t* tests were observed for the three tests that involved the slopes for blurred targets on increments, $t(min) = 3.9$, $p(min) = 0.008$. The other three post hoc tests were not significant. The same pattern of results was observed for the SR stimulus. Here the average slopes were 1.27 and 0.75 for blurred-edge ellipses presented on increments and decrements and 0.94 and 0.78 for sharp-edge ellipses presented on increments and decrements, respectively. Only the three tests involving the deviating slopes for blurred-edge ellipses on increments were statistically significant from the rest, $t(min) = 3.5$, $p(min) = 0.01$.

Control experiment: Matching to an external reference

One could argue that the effects obtained with mutual matching might have exaggerated the differences between targets on increments and decrements because the target and the test ellipses were both presented within their own context. We therefore conducted a control experiment that was similar to the first part of the main experiment in which we asked observers to adjust an external reference so as to match each of the test ellipses separately. We also repeated the mutual matching experiment for the proper ellipses in order to be able to relate the results to those of the previous experiment. We did this only for the sharp-edge ellipses because due to their nonsurface-like appearance the blurred ellipses could not be satisfyingly matched with the solid reference region.

We observed a high degree of consistency between the two replications of the mutual matching experiment. We will consider the intercepts at zero incremental luminance as our standard of comparison between the different experiments because they provide an estimate for the perceived lightness of the checks themselves in the absence of an elliptical target (zero increment). This estimate of check lightness can be compared to the matches observed in the first part of the main experiment.

The results for the control experiment comparing the external and the mutual matching task are depicted in Figure 6. In the AC, the average intercepts for mutual matching on dark and light checks were 42 and 101 cd/m^2 in the control experiment (Figure 6A, left). These values were exactly identical to the values observed in the main mutual matching experiment (Figure 3B, right). For the external matching, we observed intercept values of 58 and 115 cd/m^2 for matches on the dark and the light checks. The statistical significance of the observed effects was tested by a two-by-two repeated-measures ANOVA with the factors target location (dark vs. light) and matching task (mutual vs. external). The values from the external matching were slightly higher than those from the mutual matching (86 vs. 72 cd/m^2), $F(1, 7) = 11$, $p = 0.01$. But, importantly, the interaction between the factors task and target location was not significant. The difference between lightness matches for targets located on increments and decrements was 59 cd/m^2 in the mutual matching task and 57 cd/m^2 in the external matching task. In the SR stimulus, the average intercepts for mutual matching on dark and light squares were 53 and 76 cd/m^2 in the control experiment (Figure 6B, left) and 48 and 79 cd/m^2 in the main experiment (Figure 5A, right). For the external matching, values of 65 and 92 cd/m^2 were observed for matches on the dark and light squares. Again, match luminances were overall higher in the external than in the mutual matching task (78 vs. 64 cd/m^2), $F(1, 7) = 14$, $p = 0.007$, but the interaction effect was not significant. The differences between targets on increments and on decrements were 23 cd/m^2 for the mutual and 27 cd/m^2 for the external matching tasks. So the difference in perceived lightness between targets on incremental or decremental checks was not influenced by the type of matching task.

The absolute magnitude of the intercepts at zero incremental luminance in the external matching task were in good agreement with the actual matches that were obtained in part one of the main experiment for the checks in the SR stimulus and the AC. The observed match luminances for dark and light checks were 58 and 113 cd/m^2 for the AC stimulus, and the estimated intercepts at zero incremental luminance were 58 and 115 cd/m^2 in the external matching task. For the SR stimulus, the match luminances were 51 and 95 cd/m^2 and the estimated intercepts were 65 and 92 cd/m^2. These numbers indicate a high degree of consistency between tasks, in particular because the control experiment included only three out of the first seven observers.

Discussion

The present experiment was designed to test whether changes in the properties of a target will affect its perceived lightness. At the same time, the local contrast of the target was held constant to rule out potentially confounding effects of the context.

The first result was that, in the present experiment, contrast and assimilation effects were of similar magnitude. The apparent lightness difference between the critical checks of interest in the AC (Figure 1A) was virtually identical to that observed for elliptical targets superimposed on those checks (Figure 1B). This result was specific for the AC stimulus. For the SR display, we observed smaller assimilation than contrast effects. The strong assimilation measured on the AC stimulus is much larger than previously observed (Rudd, 2010; Shapley & Reid, 1985). The measurement of the magnitude of the assimilation effect was replicated in two independent repeats of the mutual matching task and in an external matching task. We also replicated the previously reported difference in magnitude between assimilation and contrast with the SR stimulus. We conclude that the observed difference in the magnitude of the assimilation effect between stimuli is genuine and that it might be due to the higher degree of complexity in the AC with respect to 3-D scene geometry and to the greater variety of different surface reflectances (articulation).

The second result was that sharp-edge and blurred-edge ellipses behaved fundamentally differently as far as their perceived lightness is concerned. Elliptical targets with a sharp edge underwent the same lightness difference as the checks on which they were superimposed whereas the lightness difference between blurred ellipses on light and dark checks was reduced by a factor of three (60 vs. 19 cd/m^2 average cumulated sum of differences, Figures 3 and 5A). This shows that the influence of the context on the lightness of a target is not fixed but instead can be flexibly modulated depending on the properties of the target region.

Assimilation and contrast: Models and mechanisms

In our experiments for each pair of targets that had the same luminance in Figure 3, the local contrast with the surrounding checks was the same whether the target was placed on a dark (decrement) check surround or on a light (increment) check surround. Thus, any difference between the lightnesses of the target ellipses in each pair had to be caused by processes other than local contrast because that was the same for each target in such a pair.

The observed effects hence require an explanation that involves remote contextual effects on the target region. Among others (Jameson & Hurvich, 1975; Rudd, 2013; Rudd & Zemach, 2004), Reid and Shapley (1988) have formalized this idea by expressing the lightness of an image region as the weighted sum of local and remote contrast edges. To rephrase their model for the present stimuli, we label the target and comparison ellipses as T and C and their surround checks as S_T and S_C, respectively. Their respective remote backgrounds are labeled B_T and B_C (as in Figure 7). According to Reid and Shapley, the primary determinant of the lightness of ellipse T would be its local contrast with the check, C_{T,S_T}, and that would be complemented by the remote contrast edge between the check and the check's surround, $C_{S_T,B_T} : \Psi(T) = C_{T,S_T} + \alpha \times C_{S_T,B_T}$. Although the local contrast term received a weight of 1, the remote contrast term usually received a weight of α that was smaller than 1. Just as a reminder, the remote contrast term needed to be included in the lightness prediction because with equiluminant checks ($L_{S_T} = L_{S_C}$) and equiluminant elliptical targets ($L_T = L_C$), the local contrasts would also be identical $C_{T,S_T} = C_{C,S_C}$. Hence, a lightness model based on local contrasts only would make the prediction of equal lightness for the elliptical target, which does not correspond to our and other empirical data (Rudd, 2010; Shapley & Reid, 1985). Different from what has been previously reported, for the proper ellipses in the AC, our data suggest a weight of $\alpha = 1$ for the remote term in the equation. This is because the local contrasts between ellipses and checks were equal $C_{T,S_T} = C_{C,S_C}$, and therefore the lightness prediction for T and C reduces to $\Psi(T) = \alpha \times C_{S_T,B_T}$ and $\Psi(C) = \alpha \times \alpha^* C_{S_C,B_C}$. We observed perceptual differences of comparable size between $\Psi(C)$ and $\Psi(T)$ and between $\Psi(S_C)$ and $\Psi(S_T)$; therefore the weight given to the remote term is inferred to be 1. There are two problems that remain open with that reasoning: First, the perceived lightness of $\Psi(S_T)$ or $\Psi(S_C)$ is not the same as $\alpha \times C_{S_T,B_T}$ and $\alpha \times C_{S_C,B_C}$, but rather might itself be a combination of local and remote terms. And second, the background as it is indicated in Figure 7, was supposed to be identical in the SR and AC stimulus. However, for the SR stimulus,

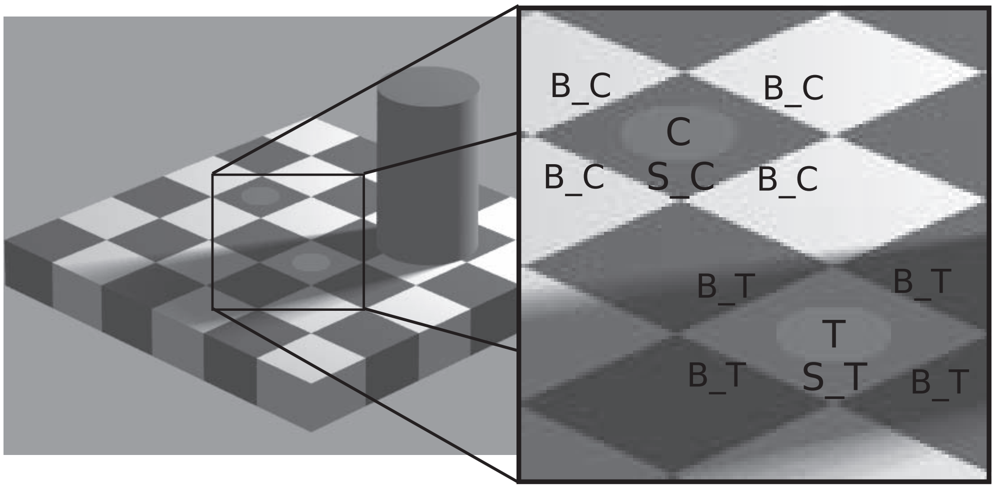

Figure 7. Naming convention for weighted contrast computation in AC. T and C refer to target and comparison regions. The ellipse in the shadow was randomly assigned as a target region as both ellipses inside and outside the shadow served as target and comparison regions in different trials. S_T and S_C indicate the respective surround regions for the target and comparison ellipses, and B_T and B_C the respective remote background regions.

the effect of the remote context was not as big as for the AC stimulus as indicated by smaller lightness differences for assimilation than for contrast effects. Thus, the background that is relevant for the computation of lightness of the targets in the AC must involve more than just the directly adjacent edges. In fact, in a previous experiment with customized checkerboards, in which the check's surround was composed of heterogeneous reflectances, we have observed that check lightness was better predicted by considering all eight adjacent checks instead of just the four checks that shared a border with the target check (Maertens & Shapley, 2013). The articulatedness, i.e., the number of corners and edges in the neighborhood of the target checks, is one of the major differences between the AC and SR stimulus, and it might have contributed to the observed difference in assimilation effects between the two types of stimuli. This question needs to be addressed in future experiments.

A similar but more elaborate account of this kind is the edge-integration model (e.g., Rudd, 2013; Rudd & Zemach, 2004), in which edges are weighted differently with respect to their influence on a target as a function of their polarity and their distance to the target. These long-range interactions are thought of as operating at an early level of visual processing whereby the border signals at the checks' boundaries propagate across space and exert their influence on the target region (Rudd, 2014). According to this account, the strength of the contextual effect would decrease with increasing distance between the target and the inducing boundary. This would be in agreement with the previously reported differences in effect size between contrast and assimilation effects (Reid & Shapley, 1988; Rudd, 2010). Edge-integration models do not predict any differences in lightness between targets with sharp or blurred edges. This is a weakness of the current models that needs to be addressed.

Multiscale spatial filtering accounts of lightness or brightness perception, such as the oriented-difference-of-Gaussian model (Blakeslee & McCourt, 2004) would also predict the assimilation effects to be smaller than the contrast effect in our stimuli. This is because the filter that is tuned to the size of the target will respond equally for ellipses presented inside and outside the shadow because they are identical in contrast. Only larger filters that respond to the entire checks will give a differential response, and that differential response will be integrated with that of the filter responding to the target so that overall an assimilation effect smaller than the contrast effect will result.

Alternatively, one could think of the context as a region of common illumination that is identified in a yet not understood process of retinal image segmentation. Such a segmentation mechanism is assumed in models such as anchoring theory (e.g., Gilchrist et al., 1999; Gilchrist & Radonjic, 2010) and has been advocated by others albeit not in elaborated theories (Singh, 2004; Zeiner & Maertens, 2014). Such segmentation may be needed to explain the perception of lightness through partially transparent media but may not be necessary for explaining lightness perception in shadows (Maertens & Shapley, 2013) as in the AC pattern.

Yet another class of lightness models involves the explicit estimation of the illumination, or light source, in addition to the surfaces' reflectances (e.g., Allred & Brainard, 2013; Bloj et al., 2004; Murray, 2013). The models that derive lightness based on the explicit or implicit consideration of illumination differences would predict that all regions within one region of illumination undergo the same lightness computation regardless of their distance to an illumination boundary. However, such theories do not allude to the lightness computations that are needed to account for measurements such as those in this paper.

Neural mechanisms

The different processes that lead to perceived lightness likely are generated in many different areas of the visual system. Classically, contrast is a monocular computation (Heinemann, 1955; Whittle & Challands, 1969) that is likely determined at retinal and early cortical levels. The spreading influence of assimilation may be seen in a fraction of V1 neurons (Kinoshita & Komatsu, 2001; Paradiso et al., 2006; Reid & Shapley, 1988). However, our finding that assimilation may be gated by the perceptual interpretation of the target suggests that higher-level cortical areas, such as V4 and lateral occipital complex, that are sensitive to perceptual organization (Grill-Spector & Malach, 2004; Orban, 2008; Stanley & Rubin, 2003) may have an influence on assimilation signals in early cortex. The present experiments do not probe the spatial extent of the contextual interactions that controlled lightness, but previous work indicated that besides the contrast with adjacent edges, the context that mattered most was the set of contours of nearest neighbors (Maertens & Shapley, 2013; Rudd, 2013; Rudd & Zemach, 2007). Thus, one hypothesis for the mechanism of assimilation is that it is polarity-sensitive mutual suppression between cortical cells or networks in the visuotopically mapped visual cortical areas such as V1, V2, or V4. Further neuroscientific studies of the mechanisms underlying assimilation are needed.

Blurred versus proper ellipses

Blurred- and sharp-edge ellipses were perceived as profoundly different in lightness in both the AC and the SR stimuli. However, they differed not only in their mean perceived lightness. For ellipses with sharp boundaries, increments were sometimes matched with decrements. That can be read from Figures 3, 5A, and 6A. The dotted horizontal line in the figures indicates the luminance of the checks on which the targets and the matches were superimposed. The targets were always increments relative to the check's luminance, but for targets located on decremental checks, the match ellipse located on incremental checks was sometimes adjusted to be a decrement. This can be read from the leftmost two or three red data points in Figures 3B, 5A right, and 6A left because they are located below that dotted line and hence are decrements with respect to their checks. Such matches were not observed for the blurred ellipses.

We think that the observed differences between sharp- and blurred-edge ellipses result from differences in the perceptual interpretation of their underlying physical causes. Sharp-edge ellipses are perceptually consistent with solid disks that lie on top of the check's surface whereas blurred-edge ellipses are perceptually consistent with the cone of a spotlight that falls on the check's surface. Hence, as one of our reviewers has pointed out, it might be more adequate to refer to the perceived intensity of the sharp-edge ellipses as lightness and to the perceived intensity of the blurred-edge ellipses as brightness (see Arend & Spehar, 1993a, 1993b). In the above paragraph, we have outlined how the visual system might compute the lightness of surfaces using local and remote contrast signals. The goal of that computation is to stabilize the perception of relevant object properties, such as the reflectance of a surface against fluctuations in the input signal (luminance) that are caused by incidental changes in viewing conditions (illumination). Here, we propose that this computation is performed only for image regions that are interpreted as surfaces and hence have a stable reflectance property that needs to be computed relative to the rest of the input luminances.

For other, nonsurface-like external objects, that computation would not be adequate. If the blurred ellipse is interpreted as the cone of a spotlight, then its perceived intensity is independent of the overall illumination level and hence from the rest of the luminances in the scene. To determine their brightness, the remote term would receive relatively less weight, and the main contribution would be made by the local contrast term. That reasoning is consistent with our data. The local contrast term reflects the interaction between the perceived lightness of the underlying surface and the spotlight because the reflectance of the underlying surface will determine how much of the light of the spotlight will be reflected.

We did not test these presumed differences in the perceptual interpretation of sharp- and blurred-edge ellipses explicitly, and other interpretations might as well be possible. However, here we assume that the difference in lightness between checks and proper ellipses results from computations that compensate for illumination differences by taking the contrast between targets into account.

We think this reasoning is indirectly supported by the finding that for the sharp-edge ellipses increments were sometimes matched with decrements. We would argue that the lightness of the sharp-edge ellipses has been translated into a stable perceptual attribute of a solid surface, and that attribute, *lightness*, was independent of the contrast sign at the ellipse's boundary. This is admittedly a far-reaching interpretation, which needs to be exposed to experimental test in the future.

When we suggested that the visual system responds to the blurred ellipses as if they were cones from a spotlight, then this does not involve an explicit inversion of the image to estimate the external physical situation. The blurred boundaries might simply signal the absence of a solid surface, and this absence might be sufficient to change the computation from a lightness to a brightness computation. However, at present, we cannot rule out the possibility that mechanisms such as scission may have affected the lightness of the targets as well (Ekroll & Faul, 2013; Schmid & Anderson, 2014) as they were still homogeneous targets embedded in locally homogeneous surrounds and hence perceptually ambiguous.

An objection that might be raised is that the sharp-edge and blurred-edge ellipses differed in their activation of early visual pathways because of the different spatial profiles of their boundaries, and this activation difference may account for the lightness differences. We think that the data in Figures 3 and 5 argue against this objection. The slopes of the functions relating match and target luminance were similar for sharp-edge and blurred-edge ellipses located on decrements (checks outside the shadow) and for sharp-edge ellipses located on increments. Slightly higher slopes were observed for blurred-edge ellipses located on increments. These data suggest that the sharp-edge and blurred-edge targets were roughly equally effective in exciting early visual processes because for every incremental step in target intensity observers adjusted a comparable step in match intensity. If anything, blurred-edge ellipses were slightly more effective in that respect, but this cannot explain the observed difference between targets on increments and decrements for blurred-edge versus sharp-edge ellipses. We designed the sharp-edge and blurred-edge ellipses so as to equate flux by equating the volume under their envelope (see Methods), and identical slopes for both targets on decrements indicate that this was an adequate choice.

Conclusion

Our results show that an image manipulation that changes the perceptual interpretation of a target can have significant effects on perceived lightness, one important property of a visually perceived surface. This indicates that a seemingly elementary property such as lightness is coupled to perceptual organization as has been suggested previously (Gilchrist, 2006; Wallach, 1935; Wuerger, Shapley, & Rubin, 1996). Such coupling is suggestive of possible feedback pathways in perceptual systems between higher-level and lower-level computations. The presence of such feedback does not rule out that lower-level mechanisms have an important role to play in lightness perception. Rather, one would expect that top-down feedback influences would become more important when stimuli are more complicated and/or ambiguous. Our finding that assimilation was stronger when the targets were perceived as objects and that assimilation was stronger for object-like targets on checkerboards versus uniform backgrounds does not change the fact that contrast is important for perceived lightness (Blakeslee & McCourt, 2004; Maertens & Shapley, 2013; Rudd, 2010; Singh, 2004; Wallach, 1948; Zeiner & Maertens, 2014). It is not an either/or situation; both lower-level and higher-level mechanisms appear to influence lightness. Perhaps some of the controversy in the area of lightness perception (reviewed by Kingdom, 2011) was caused by the fact that contrast and assimilation effects were weighted differently in the many different stimulus configurations that have been used to study lightness perception.

Keywords: surface lightness, mid-level vision, assimilation, context

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References

Adelson, E. (1993). Perceptual organization and the judgment of brightness. *Science, 262,* 2042–2044.

Allred, S., & Brainard, D. (2013). A Bayesian model of lightness perception that incorporates spatial variation in the illumination. *Journal of Vision, 13*(7): 18, 1–18, http://www.journalofvision.org/content/13/7/18, doi:10.1167/13.7.18. [PubMed] [Article]

Anderson, B., & Winawer, J. (2005). Image segmentation and lightness perception. *Nature, 434,* 79–83.

Arend, L., & Spehar, B. (1993a). Lightness, brightness, and brightness contrast: 1. Illumination variation. *Perception & Psychophysics, 54,* 446–456.

Arend, L., & Spehar, B. (1993b). Lightness, brightness, and brightness contrast: 1. Reflectance variation. *Perception & Psychophysics, 54,* 457–468.

Blakeslee, B., & McCourt, M. (2004). A unified theory of brightness contrast and assimilation incorporating oriented multiscale spatial filtering and contrast normalization. *Vision Research, 44,* 2483–2503.

Bloj, M., Kersten, D., & Hurlbert, A. (1999). Perception of three-dimensional shape influences colour perception through mutual illumination. *Nature, 402,* 877–879.

Bloj, M., Ripamonti, C., Mitha, K., Hauck, R., Greenwald, S., & Brainard, D. (2004). An equivalent illuminant model for the effect of surface slant on perceived lightness. *Journal of Vision, 4*(9):6, 735–746, http://www.journalofvision.org/content/4/9/6, doi:10.1167/4.9.6. [PubMed] [Article]

Boyaci, H., Doerschner, K., Snyder, J., & Maloney, L. (2006). Surface color perception in three-dimensional scenes. *Visual Neuroscience, 23,* 311–321.

Ekroll, V., & Faul, F. (2013). Transparency perception: The key to understanding simultaneous color contrast. *Journal of the Optical Society of America A, 30,* 342–352.

Gilchrist, A. (1977). Perceived lightness depends on perceived spatial arrangement. *Science, 195,* 185–187.

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

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

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., & Radonjic, A. (2010). Functional frameworks of illumination revealed by probe disc technique. *Journal of Vision, 10*(5):6, 1–15, http://www.journalofvision.org/content/10/5/6, doi:10.1167/10.5.6. [PubMed] [Article]

Grill-Spector, K., & Malach, R. (2004). The human visual cortex. *Annual Review of Neuroscience, 27,* 649–677.

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

Hillis, J., & Brainard, D. (2007). Distinct mechanisms mediate visual detection and identification. *Current Biology, 17,* 1714–1719.

Jameson, D., & Hurvich, L. (1975). From contrast to assimilation: In art and in the eye. *Leonardo, 8,* 125–131.

Kingdom, F. (2011). Lightness, brightness and transparency: A quarter century of new ideas, captivating demonstrations and unrelenting controversy. *Vision Research, 51,* 652–673.

Kinoshita, M., & Komatsu, H. (2001). Neural representation of the luminance and brightness of a uniform surface in the macaque primary visual cortex. *Journal of Neurophysiology, 86,* 2559–2570.

Knill, D., & Kersten, D. (1991). Apparent surface curvature affects lightness perception. *Nature, 351,* 228–230.

Mach, E. (Ed.). (1886). *The analysis of sensations.* New York: Dover.

Maertens, M., & Shapley, R. (2013). Linking appearance to neural activity through the study of the perception of lightness in naturalistic contexts. *Visual Neuroscience, 30,* 1–10.

Maertens, M., & Wichmann, F. (2013). When luminance increment thresholds depend on apparent lightness. *Journal of Vision, 13*(6): 21, 1–11, http://www.journalofvision.org/content/13/6/21, doi:10.1167/13.6.21. [PubMed] [Article]

Murray, R. (2013). Human lightness perception is guided by simple assumptions about reflectance and lighting. *Proceedings of the Society of Photographic Instrumentation Engineers (SPIE), special section on Human Vision and Electronic Imaging XVIII.* doi:10.1117/12.2001782

Orban, G. (2008). Higher order visual processing in macaque extrastriate cortex. *Physiological Reviews, 88,* 59–89.

Paradiso, M., Blau, S., Huang, X., MacEvoy, S., Rossi, A., & Shalev, G. (2006). Lightness, filling-in, and the fundamental role of context in visual perception. *Progress in Brain Research, 155,* 109–123.

Purves, D., Shimpi, A., & Lotto, R. (1999). An empirical explanation of the Cornsweet effect. *The Journal of Neuroscience, 19,* 8542–8551.

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

Radonjic, A., Todorovic, D., & Gilchrist, A. (2010). Adjacency and surroundedness in the depth effect on lightness. *Journal of Vision, 10*(9):12, 1–16, http://www.journalofvision.org/content/10/9/12, doi:10.1167/10.9.12. [PubMed] [Article]

Reid, C., & Shapley, R. (1988). Brightness induction by local contrast and the spatial dependence of assimilation. *Vision Research, 28,* 115–132.

Rudd, M. (2010). How attention and contrast gain control interact to regulate lightness contrast and assimilation: A computational neural model. *Journal of Vision, 10*(14):40, 1–37, http://www.journalofvision.org/content/10/14/40, doi:10.1167/10.14.40. [PubMed] [Article]

Rudd, M. (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]

Rudd, M. (2014). A cortical edge-integration model of object-based lightness computation that explains effects of spatial context and individual differences. *Frontiers in Human Neuroscience, 8,* 1–14.

Rudd, M., & Zemach, I. (2004). Quantitative properties of achromatic color induction: An edge integration analysis. *Vision Research, 44,* 971–981.

Rudd, M., & Zemach, I. (2007). Contrast polarity and edge integration in achromatic color perception. *Journal of the Optical Society of America, 24,* 2134–2156.

Schmid, A., & Anderson, B. (2014). Do surface reflectance properties and 3-D mesostructure influence the perception of lightness? *Perception & Psychophysics, 14,* 1–24.

Shapley, R., & Reid, C. (1985). Contrast and assimilation in the perception of brightness. *Proceedings of the National Academy of Sciences, USA, 82,* 5983–5986.

Singh, M. (2004). Lightness constancy through transparency: Internal consistency in layered surface representations. *Vision Research, 44,* 1827–1842.

Stanley, D., & Rubin, N. (2003). Higher order visual processing in macaque extrastriate cortex. *Neuron, 37,* 323–331.

Wallach, H. (1935). Über visuell wahrgenommene bewegungsrichtung [Translation: On the visually perceived direction of motion]. *Psychologische Forschung, 20,* 325–380.

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

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

Whittle, P., & Challands, P. (1969). The effect of background luminance on the brightness of ashes. *Vision Research, 9,* 1095–1110.

Wuerger, S., Shapley, R., & Rubin, N. (1996). "On the visually perceived direction of motion" by Hans Wallach: 60 years later. *Perception, 25,* 1317–1367.

Zeiner, K., & Maertens, M. (2014). Linking luminance and lightness by global contrast normalization. *Journal of Vision, 14*(7):3, 1–15, http://www.journalofvision.org/content/14/7/3, doi:10.1167/14.7.3. [PubMed] [Article]