Supplemental Material: The Effect of Photometric and Geometric Context on Photometric and Geometric Lightness Effects

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Orientation Matching Experiment

Overview

The purpose of this experiment was to check that our disparity manipulations led to reasonably veridical perceived orientations for the background context planes and probe tabs. The same observers who participated in Experiment 2 indicated the perceived orientations of the context planes and of the probe tabs.

Methods

Observers

The five observers from Experiment 2 participated in this experiment. The conditions of this experiment were randomly interleaved with the conditions of Experiment 2.

Setup and Stimuli

The stimuli were presented on the same stereo apparatus used in Experiments 1 and 2. The same context angles and probe tab orientations used in Experiment 2 were presented binocularly. The luminance of the probe tab was always set to its maximum value, 238.39 cd/m2. The rendered illuminants for the top and bottom contexts were [238.39 8.66] cd/m², corresponding to the largest difference used in Experiment 2.
The monitor in the matching chamber located to the right of the observer displayed a green circle, 50 mm in diameter. The diameter was marked with a thin white line, which could be rotated around the center of the circle. At the beginning of each trial, this line was set to a horizontal position. Instructional text appeared above the circle. The instructions are provided in the online supplemental material available at http://color.psych.upenn.edu/supplements/lightness_photo_geo/.

**Procedure**

Observers were asked to view the stimuli and imagine what they would look like when viewed from the left side. Their task was to match the orientation of the various surfaces in the stimulus. On each trial, text on the monitor in the matching chamber indicated whether the observer should match the orientation of the top context plane, the bottom context plane, or the probe tab. Observers used a game pad to rotate the line in the green circle until it matched the orientation of the relevant surface, as it would appear if seen from the left. Lines rotated counterclockwise relative to horizontal were recorded as positive angles and lines rotated clockwise were recorded as negative angles (Figure S1). Note that there is a 180° ambiguity in the response orientation, relative to the 360° specification of the orientation of each stimulus.

Observers were tested in three experimental blocks. In each block, only one context angle was presented (45°, 90°, or 180°). Each probe tab was presented three times at each possible orientation. The order of surfaces to be matched was randomized within a block.
**Figure S1. Sign convention for the orientation matching experiment.**

When the line was rotated counterclockwise from horizontal, it was assigned a positive angle. When it was rotated clockwise from horizontal, it was assigned a negative angle. Because the matching line extended in both directions from the center of the matching circle, the matches are ambiguous with respect to the addition or subtraction of multiples of 180°.

**Results**

The raw matching data were adjusted to conform to the convention used to specify the orientation of background planes and probe tabs in the main manuscript. In making the adjustment, the 180° ambiguity present in the matches was resolved to bring the adjusted angle closest to that of the to-be-matched stimulus.

Matches for one observer from the 90° context angle condition are plotted in Figure S2. The black diagonal line is the unity line. Points that fall on this line are veridical matches. The blue line is the best-fit line through the origin. The slope of the best-fit line, 0.83 in this case, was taken as a measure of the observer's ability to perceive surface orientation. Deviations of the slope from 1 indicate misperception of surface orientation. Generally speaking, this observer perceived surface orientation in our stereo display quite well.

* The raw matching data for each observer are tabulated in the online supplemental material available at

http://color.psych.upenn.edu/supplements/lightness_photo_geo/.
Figure S2. Orientation matching results for one observer and context angle. The observer's matches are plotted as a function of the rendered angle. The black diagonal line indicates veridical matches, and the blue line is the least-squares linear fit to the data. Open symbols represent matches made to either the upper context or tabs in front of the upper context; closed symbols represent the corresponding matches for the bottom context. The shape indicates whether the match was to a context surface or a probe tab. Error bars are +/- 1 SEM. Similar plots for all observers and context angles can be found in the online supplemental material at

http://color.psych.upenn.edu/supplements/lightness_photo_geo/.

Across observers and conditions, the slopes of the best fit lines ranged from 0.71 to 1.10. Across observers, the mean slopes for the 45°, 90°, and 180° context angle conditions were 0.90, 0.89, and 0.92. The mean slopes for each observer across context angles ranged from 0.81 to 0.94. Our conclusion from this experiment is that misperception of rendered angles is not an important consideration in interpreting the data from our lightness matching experiments.
Pilot Matching and 2AFC Experiment

Overview

In a set of pilot experiments, we tested five observers using a matching response paradigm and a 2AFC response paradigm. In the matching experiment, observers were tested with a subset of conditions used in Experiment 1. In the 2AFC experiment, observers made luminance judgments between pairs of tabs that differed in orientation, but shared the same retinal surround. This experiment allowed us to check that the same qualitative pattern of results was obtained with both methods, as well as to refine the methods we used for the main experiments.

Methods

Observers

Five observers (1 male, 4 female, mean age = 24) participated in these experiments. Each observer came to the lab for 3-5 sessions and was compensated for his or her time. All observers were screened using the same procedures and criteria as those reported in Experiments 1 and 2. None participated in either Experiment 1 or 2. The stimuli in both experiments were viewed under binocular and monocular viewing conditions. All observers were tested binocularly in the matching experiment first. The remaining conditions for both the matching and 2AFC experiments were randomly interleaved and tested subsequently.
Setup and Stimuli

The stimuli were presented on the same stereo apparatus used in Experiments 1 and 2. Observers viewed the stimuli under both binocular and monocular viewing conditions. For the monocular conditions, a piece of felt was taped over one of the openings in the faceplate, and the stimuli were rendered just as in the binocular conditions. The stimuli were similar to those in Experiments 1 and 2, except for the changes detailed below.

The context planes were 210 mm x 200 mm in the three-dimensional scene space and were rendered at a 90° context angle. They consisted of 116 individual polygons each. The upper context polygons had luminances in the range [15.89, 228.39] cd/m², and the lower context polygons had luminances in the range [0.58, 8.66] cd/m². The 116 luminances within a context plane were drawn with equal log spacing.†

In the matching experiment, a 35 mm x 35 mm square probe tab was rendered at the ±135° and ±45° tab angles, just as in Experiment 1. No geometric manipulation to maintain the right eye image constant was used in the pilot

† Due to a programming error, the luminance values were not as specified for all observers in all conditions. The exceptions were as follows. For all observers, in the matching experiment under binocular viewing conditions, the upper context luminances were in the range [17.46, 261.86] cd/m², and the lower context luminances were in the range [0.63, 9.45] cd/m². This was also true for Observer A1 in the 2AFC experiment.
matching experiment, so in both monocular images slight changes in the shape of the probe tab co-occurred with changes in orientation. The tab was rendered at the following luminance values for the binocular condition: [0.60 1.34 2.84 6.04 12.84 27.29 58.00 123.23 261.86] cd/m².‡

For the 2AFC experiment, instead of a single probe tab, two 35 mm x 35 mm square tabs were rendered near the center of the stimulus along the ridge between the contexts. The tabs always shared the same retinal background in the monocular image, but had different orientations in the binocular image. Thus, a -135° tab always appeared next to a -45° tab, and a 135° tab always appeared next to a 45° tab. The tabs could take on any luminance value between 0.58 and 238.39 cd/m².§ The centers of the tabs were 82.6 mm apart from each other in the horizontal direction.

Procedure

The procedure for the matching experiment was the same as in Experiment 1, and the instructions are available in the online supplemental material at http://color.psych.upenn.edu/supplements/lightness_photo_geo/.

For the 2AFC experiment, observers were asked to indicate via a gamepad whether the left or right tab appeared lighter. On each trial, one of the two patches

‡ For the monocular condition, the following values were used for all observers: [0.58 1.23 2.60 5.53 11.73 24.91 52.89 112.28 238.39] cd/m².

§ This range was 0.63 and 261.86 cd/m² for Observer A1.
was designated as the *reference tab*. Its luminance was fixed at one of four values: [1.23, 5.53, 24.91, 112.28] cd/m². The luminance of the other *match tab* was adjusted via a 1-up 1-down staircase procedure (Levitt, 1971) to estimate a luminance perceived to be equal to the reference tab luminance (point of subject equality or PSE). This resulted in a total of 16 interleaved staircases in each block (2 contexts x 2 reference tab orientations x 4 reference luminances). Whether the reference or the match tab was on the left was randomly chosen on every trial.

In the matching experiment, there were 108 trials per block (4 tab orientations x 9 tab luminances x 3 repetitions). In the 2AFC experiment, there were 800 trials per block (16 staircases x 50 trials per staircase).

**Results**

The data from the matching experiment are very similar to those from the corresponding conditions in Experiment 1. Data from tab luminances that did not elicit any out-of-range responses are plotted in Figure S3. In Panel A, the mean matches across repetitions and observers for the binocular condition are plotted as a function of tab luminance, in the same format as Figure 2D. As in Experiment 1, matches monotonically increase with tab luminance. The geometric effect of tab angle can also be seen, and closely resembles the pattern shown in Figure 2D.

**Figure S3. Pilot matching experiment data.** A) Mean matches across replications and observers, same format as the panels of Figure 2 of the main

** For Observer A1, these values were [1.34, 6.04, 27.29, 123.23] cd/m².
paper. B) Mean binocular matches as a function of the probe tab angle, in the same format as Figure 3 of the main paper. C) Left eye monocular matches, same format as B. D) Right eye monocular matches, same format as B. Error bars indicate +/- 1 SEM.

Panels B, C, and D plot the mean matches as functions of the probe tab angle, for the binocular and two monocular viewing conditions. In all three conditions, there is a photometric effect as the tabs move from being in front of the upper context plane to being in front of the lower context plane. There is a clear geometric effect of the probe tab angle for the binocular conditions (Panel B), but not for the monocular conditions (Panels C and D).

For the 2AFC experiment, the data from each staircase were fit with a logistic function using routines from the Palamedes MATLAB toolbox (Prins & Kingdom, 2009). PSEs were estimated from the fitted functions as the level of the match tab required for a 50% probability of a “match lighter than reference” response.

PSEs for one observer are plotted in Figure S4, and the figures for all observers for both matching and 2AFC can be found in the online supplemental materials available at

http://color.psych.upenn.edu/supplements/lightness_photo_geo/. In both panels, each point plots the reference patch luminance and corresponding PSE from each staircase. The data are plotted so that points lying above the diagonal indicate a geometric effect in the expected direction. Points that fall along the diagonal
indicate conditions where the luminance matches were veridical, and there was no geometric effect of the tab angle.

**Figure S4: 2AFC data for one observer.** Panel A shows the 2AFC data under binocular viewing conditions. Panel B shows the 2AFC data under monocular viewing conditions, with the color of the symbol indicating the viewing eye as indicated in the legend. The diagonal black line indicates unity, i.e. physical veridical matches. The data are plotted so that for both negative and positive probe tab angles, the geometric effect expected from the matching data corresponds to points above the diagonal. The dotted red line is an estimate of where the data would plot if the PSEs were predicted by the pilot matching data shown in Figure S3A.

The data for the binocular condition generally lie above the diagonal, while the data for the monocular conditions cluster around the diagonal. We quantified the geometric effect of tab angle by taking the signed Euclidian distance of the data points from the diagonal line. A Wilcoxon signed-rank test applied to these distances showed that the binocular data was significantly different from the diagonal for 4 out of 5 observers at the $p < 0.05$ level. For all observers, the same procedure indicated that the monocular data did not deviate from the diagonal for the same $p < 0.05$ criterion. We conclude that the 2AFC paradigm also shows a geometric effect of tab angle on lightness for binocular viewing, and that this effect is reduced or eliminated for monocular viewing.
The dashed line in each panel of Figure S4 is an estimate of where the binocular data would fall if the PSEs were predicted by the pilot matching data shown in Figure S3A. We linearly interpolated the curves in that figure and used the interpolated curves to estimate pairs of in-plane/out-plane probe tab intensities that corresponded to the same match. We averaged these across negative and positive probe tab angles, using the plotting convention of Figure 4. The geometric effects predicted from the matching experiment are larger than those found in the 2AFC experiment, but not tremendously so.

**Supplemental References**


Observer 7, Context Angle 90°, Slope 0.83

Figure S2
Figure S3
Obs A1, PSEs for binocular condition

Tab luminance, geometry 1 (log10 cd/m²)
Tab luminance, geometry 2 (log10 cd/m²)

Obs A1, PSEs for monocular condition

Figure S4