

Characterizing visual asymmetries in contrast perception using shaded stimuli

José Chacón

Faculty of Psychology, Complutense University of Madrid, Madrid, Spain



Miguel Ángel Castellanos

Faculty of Psychology, Complutense University of Madrid, Madrid, Spain



Ignacio Serrano-Pedraza

Faculty of Psychology, Complutense University of Madrid, Madrid, Spain
Institute of Neuroscience, Newcastle University, Newcastle upon Tyne, UK



Previous research has shown a visual asymmetry in shaded stimuli where the perceived contrast depended on the polarity of their dark and light areas (Chacón, 2004). In particular, circles filled out with a top-dark luminance ramp were perceived with higher contrast than top-light ones although both types of stimuli had the same physical contrast. Here, using shaded stimuli, we conducted four experiments in order to find out if the perceived contrast depends on: (a) the contrast level, (b) the type of shading (continuous vs. discrete) and its degree of perceived three-dimensionality, (c) the orientation of the shading, and (d) the sign of the perceived contrast alterations. In all experiments the observers' tasks were to equate the perceived contrast of two sets of elements (usually shaded with opposite luminance polarity), in order to determine the subjective equality point. Results showed that (a) there is a strong difference in perceived contrast between circles filled out with luminance ramp top-dark and top-light that is similar for different contrast levels; (b) we also found asymmetries in contrast perception with different shaded stimuli, and this asymmetry was not related with the perceived three-dimensionality but with the type of shading, being greater for continuous-shading stimuli; (c) differences in perceived contrast varied with stimulus orientation, showing the maximum difference on vertical axis with a left bias consistent with the bias found in previous studies that used visual-search tasks; and (d) asymmetries are consistent with an attenuation in perceived contrast that is selective for top-light vertically-shaded stimuli.

Introduction

Interpreting the world through the light coming to our eyes is a huge task. The visual system works hard to process the initial raw information to build up a model that approximates to the real objects' properties. One integral property of any object present in natural scenes is shading. Except when we are faced with a completely flat surface, shading is present in objects with any variation in shape, either sharp or smooth, and such variations will produce differences in the amount of light that reaches our retinas. Shading perception depends on many aspects that are related, in one way or another, to the three-dimensional shape perception or the lighting direction. It has been suggested that the visual system uses a convexity prior when extracting shape from shading (Chacón, 2004; Langer & Bühlhoff, 2001; Reichel & Todd, 1990; Thomas, Nardini, & Mareschal, 2010) and it is able to achieve robust shape estimation (Khang, Kappers, & Koenderink, 2007; Kleffner & Ramachandran, 1992; Ramachandran, 1988) although usually underestimating three-dimensionality (Khang et al., 2007; Kleffner & Ramachandran, 1992; Mingolla & Todd, 1986; Ramachandran, 1988; Todd & Mingolla, 1983). Furthermore, shape from shading could serve as a basis for grouping (Ramachandran, 1988), a property showed by elemental characteristics (as color, orientation, texture, etc.) that, jointly with evidences of parallel processing, persuaded Braun (1993) to suggest that “shape from shading” might be a texton. With regard to perceived lighting direction, the visual system uses, by default, a

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light-from-above prior (Brewster, 1826; Rittenhouse, 1786), applied from retinocentric coordinates (Kleffner & Ramachandran, 1992; Yonas, Kuskowski, & Sternfels, 1979) although it seems to be mixed with a diffuse source approximation (Schofield, Rock, & Georgeson, 2011). Furthermore, the light-from-above prior is slightly biased some degrees to the left (Gerardin, de Montalembert, & Mamassian, 2007; Mamassian & Goutcher, 2001; Sun & Perona, 1998; Symons, Cuddy, & Humphrey, 2000) and it has been shown that these preferences in orientation can be modified experimentally (Adams, Graf, & Ernst, 2004).

Lightness constancy is a process related to shading by which the visual system seems to estimate the true reflectance of an object from different luminance patterns that it receives. To perform this, the mechanisms implied in this process should counteract the distortions induced by shadows, filter's transmittance, sources of illumination, or the geometry of the object, among others (Adelson, 2000), and the whole process results in a stable lightness perception of the object. The phenomenon studied here, although inside the field of shading perception, could also be included into the lightness constancy mechanisms. In Chacón (2004) we found a contrast effect that could be explained by a *compensation* process. This process estimates approximately the true reflectance of the perceived shaded object, as it modifies the contrast produced by shading in three-dimensional objects. Interestingly, Chacón (2004) found functional *asymmetries* in this compensation process, being present for some stimulus (whose luminance pattern is interpretable as that of an object illuminated from above) and not for others (with identical but inverted luminance pattern).

The contrast effect described in Chacón (2004) was not a subtle one, since most observers could detect it with the naked eye. An example is shown in Figure 1, where the top-light circle elements on the left (usually perceived as protuberances) are perceived as having lower contrast than those on the right (top-dark, perceived as concavities). The measurement of the point of subjective equality (PSE), that is, the contrast level for the top-dark circles to be perceived with the same contrast as top-light circles, showed that top-dark circles are perceived as having 10% higher contrast than top-light circles of the same physical contrast. Search experiments showed the same asymmetry as previous studies (Enns & Rensink, 1990; Kleffner & Ramachandran, 1992; Sun & Perona, 1996a, 1997), but when goal and distractors were equated in subjective contrast, the asymmetry disappeared for five out of six observers. This result does not agree with the supposition that detection is made on the 3D shape inferred from shading; rather it suggests that the key cue was contrast.

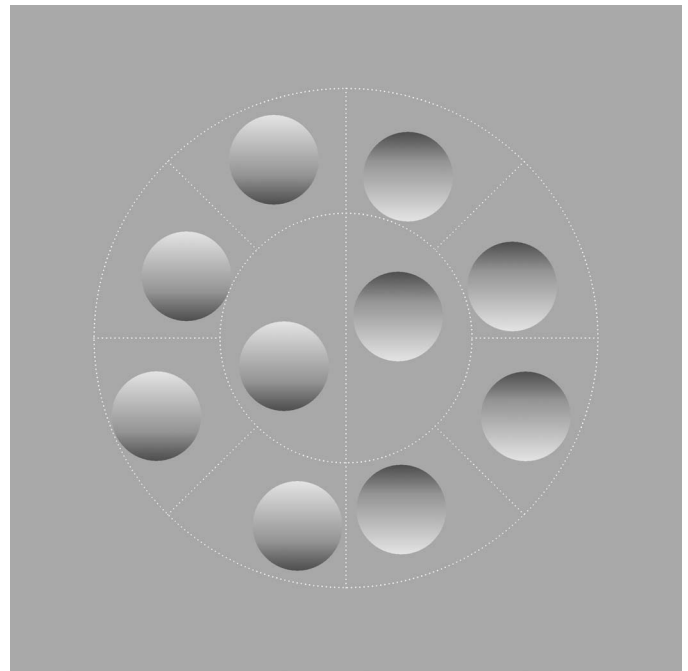


Figure 1. Example of stimuli consisted of five reference elements (top-light, on the left), and five test elements (top-dark, on the right). The circular grid is present for description purposes, and was not visible.

The differences in contrast perception pose a number of questions about the underlying mechanisms of shading perception. In the present study, in order to study these underlying shading mechanism we will perform four experiments. First, in Experiment 1 we will explore whether these differences in perceived contrast remain at any contrast level. In Experiment 2 we will study the kind of shading (or particular distributions of luminance) that elicits this asymmetry. Thus, we will study whether this effect occurs when there is a 3D perceptual interpretation of the stimuli and, specifically, whether there are differences for continuous- and discrete-shaded stimuli. Experiment 3 points to a question related to the direction (orientation) of shading (or lighting). It is known that asymmetries in visual search for shaded stimuli are dependent on the direction of shading. Thus, greater asymmetries hold for vertical orientations while they disappear for horizontal orientations (Mamassian & Goutcher, 2001; Sun & Perona, 1998; Symons et al., 2000). If, as proposed by Chacón (2004), performance in visual search tasks for shaded stimuli is related to the differences in perceived contrast, it is reasonable to expect results similar to those in search tasks, including the leftward bias. Finally, Experiment 4 will enquire about the direction (contrast reduction or magnification) and specificity of the alterations of perceived contrast found previously.

Experiment 1: Perceived-contrast asymmetries and contrast level

The aim of this experiment was to measure the effect of contrast level on the visual asymmetries in contrast perception found previously by Chacón (2004). We determine the point of subjective equality (PSE) for contrast, defined as the contrast level for one type of elements (top-dark) necessary to be perceived with equal subjective contrast as the other type (top-light), which contrast is fixed throughout the experiment. Three experimental conditions were carried out with reference elements that had constant Michelson contrasts of 0.3, 0.5, and 0.7 (low, middle, and high contrast conditions, respectively).

Methods

Participants

Four observers, two males (JC and MC) and two females (RA and ES), with normal or corrected-to-normal vision, participated voluntarily. Three subjects (two authors—JC and MC, and RA) had experience in psychophysical experiments. One of the subjects (JC) had long experience with this kind of stimuli. Subjects RA and ES were not aware of the purpose of the study. Experimental procedures were approved by Complutense University of Madrid Ethics Committee.

Apparatus

Stimuli were presented on a 20-in. Sony GDM-F520 CRT color monitor (Sony Corp., Tokyo, Japan) using a VSG2/3 graphics card (Cambridge Research Systems Ltd., Kent, UK) that provides 15-bit gray-scale resolution. All the experiments were programmed in MATLAB (MathWorks, Natick, MA). A spatial resolution of 1024×768 pixels was used, with a vertical frame rate of 120 Hz. The luminance of the monitor was gamma corrected using an optical photometer (Cambridge Research Systems). Observers sat 100 cm from the monitor, and a chin rest was used to maintain a fixed head position. All experiments were run in a dark room.

Stimuli

The elements used to build up the stimuli were circles filled out with a luminance ramp, which were perceptually consistent with convex or concave bumps illuminated from a single light source (see Figure 1). Reference elements were top-light circles, which will be referred to as reference polarity. Test elements were circles with luminance increasing in the opposite

direction (i.e., they are 180° rotated versions of reference elements), and will be referred to as opposite polarity. The diameter of the elements was 51 pixels. Luminance ranged from 0.5 to 78.5 cd/m^2 .

The three Michelson contrasts used (0.3, 0.5, and 0.7) for the reference elements gave luminance ranges from 27.7 to 51.4, from 19.8 to 59.3, and from 11.9 to 67.2 cd/m^2 , respectively for low, medium, and high contrasts. The contrast of test elements was the dependent variable for each condition and, thus, varied from trial to trial to determine the PSE. Elements were presented on a mean-luminance gray background (39.5 cd/m^2). Each stimulus consisted of an array of 10 elements arranged as shown in Figure 1. The elements were located within a 10-cell circular grid. Half of these elements appeared on the left side of the grid on random locations within the cells and had the same polarity; the other half had opposite polarity and occupied the right side of the grid. Location of reference- and opposite-polarity elements (test elements) was randomly distributed with equal probability. The grid subtended 6.1° and each element subtended 1.1° . For each condition, visual masks were constructed. These masks consisted in a circular matrix of random-luminance squares (sized 16×16 pixels) where contrast equals the contrast used in each condition. These matrices subtended 6.08° and were presented on the same mean-luminance gray background. In absence of the stimulus or the mask, the screen displayed uniform background at mean luminance.

Procedure

A spatial two-alternative forced-choice (2AFC) task was used in a contrast-discrimination paradigm in which the subjects' task was to indicate whether the stimuli on the left or on the right half of the display had higher contrast. This task renders a psychometric function analogous to those in yes/no tasks (see Figure 2A). In Experiment 1 we used one-up/two-down adaptive staircases with fixed step sizes (in Experiments 2, 3, and 4 we used one-up/one-down adaptive staircases). This procedure could give poor fittings given that most of the repetitions of the contrasts are concentrated in values above 0.5. However, the staircases showed that at least three to four dots contained most of the repetitions and those were located within the region of support (0.2–0.9). We also fitted an odd symmetric function about the value 0.5 (see Figure 2A) to estimate the PSEs so the fittings are less affected by the asymmetry in the number of repetitions per contrast around the value 0.5. Each condition used two staircases, each one with initial test contrast different enough from the reference contrast to

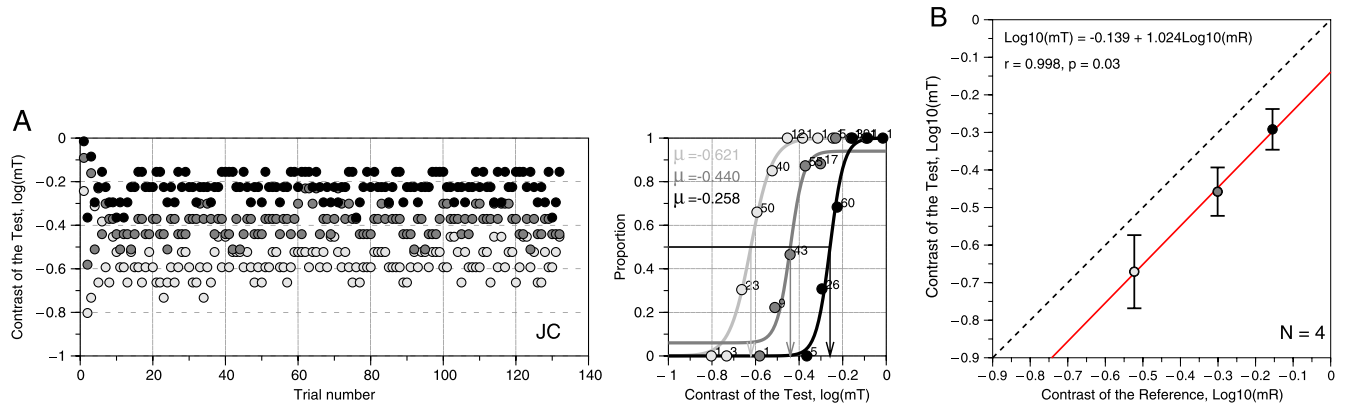


Figure 2. Results from Experiment 1. (A) Example of the staircases of one subject (JC) and the fittings of the Logistic function. Gray levels of the dots correspond to the contrast condition ($mR = [0.3, 0.5, 0.7]$). Right panel shows the proportion of times the Test stimulus is perceived with higher contrast than the Reference stimulus as a function of the contrast of the Test. Lines correspond to the Logistic fitted functions. The numbers located close to the dots correspond to the number of repetitions of each contrast of the Test. The PSEs values (μ , in log units) are shown on the top-left part of the panel. (B) Results of four subjects. Dots represent the mean ($\pm SD$) of the point of subjective equality (PSE) expressed in log units. Dashed diagonal shows the locus where the contrasts of the test and reference elements are identical. Red line is the regression line (values of regression line, Pearson correlation coefficient, and p -value are shown on top of the panel).

facilitate discriminations during the first few trials, with minimum and maximum contrast values of (0.1574, 0.5716), (0.2624, 0.8109), and (0.3674, 0.9663) for low (0.3), medium (0.5), and high (0.7) contrast conditions, respectively. The size of the steps down and up was 0.07 log units. Each staircase ran for 66 trials (132 trials per condition).

Participants undertook a preliminary staircase to familiarize with the task. In all experiments, each trial began showing a fixation cross centered on middle of the gray background. Observers were asked to maintain fixation on this point and after a lapse of 500 ms the display appeared for 50 ms, followed by a uniform background for 150 ms and a mask for 100 ms. Responses were given by pressing one of two keys on a computer keyboard.

In Experiment 1, a contrast step down was taken if the subject's response implied that test contrast was perceived higher than reference contrast two contiguous times; otherwise, a step up was taken. The experimental session lasted about 16 to 20 min and consisted of six staircases randomly interleaved, one for each combination of contrast levels (low, medium, high) and starting points (up, down).

Analysis and results

For each subject and condition, psychometric functions were fitted to the data by maximum likelihood using the Logistic function adapted from (García-Pérez (1998, Appendix A) as seen in Figure 2A:

$$\Psi(mT) = \gamma + \frac{1 - \lambda - \gamma}{1 + \exp[\beta(\alpha - \log_{10}(mT))]}, \quad (1)$$

where mT are the Michelson contrasts of the stimulus Test, $mT \in [0, 1]$; λ , the lapse rate; γ , the guess rate ($\gamma = \lambda$); guess rate and lapse rate will adopt the same value because lapses can occur with the same probability when the contrast of the Test is higher or lower than the contrast of the Reference stimulus (García-Pérez & Alcalá-Quintana, 2005). The parameters α and β are defined as follows:

$$\beta = \frac{2}{\sigma} \ln \left[\frac{1 - \lambda - \gamma - \delta}{\delta} \right] \quad (2)$$

$$\alpha = \mu + \frac{1}{\beta} \ln \left[\frac{1 - \lambda - \pi}{\pi - \gamma} \right], \quad (3)$$

where π , is the probability ($\pi = 0.5$) that corresponds to the location value μ (defined here as the PSE value, in log units); and σ is the spread of the psychometric function (with $\delta = 0.01$). We fitted the function with three free parameters, σ , λ , and μ , with constrains $\sigma > 0$, $0 \leq \lambda \leq 0.06$, and $\mu < 0$.

PSEs were obtained for a probability value of 0.5 for each fitted psychometric function. Figure 2A shows the results for one subject. Figure 2B shows the results of Experiment 1 for four subjects. This figure shows the obtained PSE (mean $\pm SD$, expressed in log units) of the test elements ($\log_{10}[mT]$) as a function of the log contrast of the reference elements ($\log_{10}[mR]$). Two-tailed t test shows significant differences between the perceived contrast of test elements and that of reference

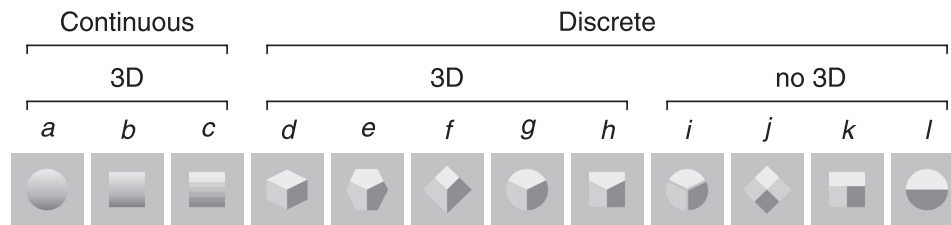


Figure 3. Reference elements used in Experiment 2.

elements; $t(3) = -2.882$; $p = 0.032$; $t(3) = -4.683$; $p = 0.009$; $t(3) = -4.919$; $p = 0.008$ for contrast conditions 0.3, 0.5, and 0.7 (-0.52 , -0.3 , -0.15 in log units), respectively. We also found a strong correlation between the perceived contrast of the test and the contrast of the reference elements ($r = 0.998$, $p = 0.03$). Figure 2B shows that there is a strong difference in perceived contrast when comparing top-light (reference) and top-dark (test) vertically shaded circles and this effect is similar for different contrast levels.

Experiment 2: Perceived-contrast asymmetries and shading patterns

In this experiment we explored if the perceived contrast asymmetry only occurs for luminance ramps (continuous shading), or if it also includes luminance configurations derived from shading in objects with sides and angles (discrete shading). To test this hypothesis, we selected a set of stimuli containing continuous and discrete shading, some of them without any 3D interpretation (see Figure 3), and we measured the asymmetry in perceived contrast for fourteen subjects. A control experiment with another group of 30 subjects was performed in order to evaluate the three-dimensional degree of the stimuli used in the experiment. Later we will compare both results.

Method

Participants

For the contrast task, 14 subjects (two males and 12 females) participated voluntarily (including authors JC and MC), with normal or corrected-to-normal vision. The experimental set-up was the same as used in Experiment 1. Thirty additional subjects (four males and 26 females) not aware of the purpose of the experiment participated in the three-dimensional evaluation task. They all had normal or corrected-to-normal vision.

Stimuli

For the contrast task, we built up 12 stimuli with different type of shading and 3D interpretation (see the versions in Figure 3). Michelson contrast for all reference stimuli was set to 0.6. Experimental setup, timing, and procedure were identical to those of Experiment 1 except where indicated in the material that follows.

We used some of the stimuli used by Sun and Perona (1996b). These authors (Sun & Perona, 1996a) proposed that, due to the relations between shape and reflectance, when stimuli suggest 3D objects, then the changes in luminance are discounted to some extent.

The elements can be grouped in three categories: those filled with a linear luminance ramp, with 3D interpretation (stimuli *a* to *c* in Figure 3); others filled with a discrete, three-level luminance, also with 3D interpretation (*d* to *h*); and other configurations with three or two levels of luminance without 3D interpretation (stimuli *i* to *l*). The elements *a* and *b* are filled with a continuous linear ramp, while stimulus *c* resembles a sampled and quantized version of *b* with seven linear steps. The elements *d*, *e* and *f* represent easily 3D-interpretable images showing three sides. Stimulus *g* and *h* can be understood as a convex corner seen through a circular or squared window (cfr. Sun & Perona, 1996b). The elements *i* to *l* acted as control stimuli. The element *i* is a broken version of *g*, in order to make its 3D interpretation more difficult. The element *l* has been used as control in shaded disks experiments (Aks & Enns, 1992; Kleffner & Ramachandran, 1992; Symons et al., 2000), and it is composed of two semi-circles with maximum and minimum luminance. Finally, the elements *j* and *k* are composed of similar gray-shaded patches, but they have no 3D interpretation.

Elements were built up so that their areas were equivalent. As said before, all the reference elements had a constant Michelson contrast of 0.6, which gave 15.8 and 63.2 cd/m^2 as minimum and maximum luminance respectively. We used the same task as in Experiment 1, where the contrast of test elements (top-dark) was the dependent variable and, thus, varied from trial to trial in order to determine the PSE. Elements were presented on a mean-luminance gray

background (39.5 cd/m²). Elements *a* and *b* were filled with a luminance ramp. The luminance of the element *c* adopted values between minimum and maximum luminance in seven linear steps; for test element, intermediate luminance values were adjusted linearly. The middle-shaded side of elements *d* to *k* was set to 44.2 cd/m² for being differentiated from the background, and their test counterparts modify only minimum and maximum luminance. Element *l* has fixed minimum and maximum luminance and the values of its test version changed while the experiment run. As in Experiment 1, test elements were 180° rotated versions (top-dark) of reference elements (top-light; see Figure 3).

For the three-dimensional rating task, we used pairs of the 12 elements described previously, so stimuli were composed of two different reference elements presented side by side. Elements showed the same patterns and luminance distributions, but greater size, subtending 2.6° each, with a gap between them of 2.5°.

Procedure

For the contrast task, we measured the PSEs for the perceived contrast using the same adaptive spatial 2AFC procedure used in Experiment 1, where one staircase per condition was used. We run 12 one-up/one-down staircases that were distributed randomly in two sessions lasting about 8 to 11 min each.

For the three-dimensional rating task, observers were required to “choose the most three-dimensional figure of each pair.” All possible pairs were showed twice, with elements placed in the two possible positions (left and right). The 66 pair combinations by two (left-right) sides of the stimuli were randomized for each subject. Stimuli were presented until the subject gave a response, and sessions lasted about 5 to 10 min.

Analysis

For the contrast task, we obtain PSEs for a probability value of 0.5 for each fitted psychometric Logistic function for each subject and condition, as in Experiment 1. Then we obtain the logarithmic difference between the contrast of reference elements (mR) and the subjectively equated contrast for test elements, (mT), so that contrast difference was obtained from $\log_{10}(\text{mR}) - \log_{10}(\text{mT})$.

In the three-dimensional rating task, in order to estimate and rank the subjective three-dimensional perception of stimuli we used the method of pair comparisons with a Bayesian version of the Bradley–Terry model (Bradley & Terry, 1952; David, 1988), and a Markov chain Monte Carlo (MCMC) approach for parameter estimation. The Bradley–Terry model

assumes that the number of elections, E_{ij} , of stimulus S_i over stimulus S_j under n_{ij} comparisons is binomial distributed with p_{ij} and n_{ij} parameters; where p_{ij} is the probability that S_i was chosen over S_j and depends of a logistic function of the difference between the perceived three-dimensionality d of both stimuli, that is, $p_{ij} = 1/[1 + \exp(-(d_i - d_j))]$. Finally, in order to estimate d and rank the subjective three-dimensionality of stimuli we used MCMC simulations with normal prior distributions. The software used for the estimation was WinBUG (Spiegelhalter, Thomas, Best, & Lunn, 2003).

Results

Figure 4 integrates the results for both tasks. The abscissa shows elements ordered by the results of the 3D rating task (arbitrary scale, for 30 subjects), while ordinate axis shows the distance in log contrast between reference and test elements ($\log_{10}[\text{mR}] - \log_{10}[\text{mT}]$) for 14 subjects.

Regarding the perceived three-dimensionality, discrete-shaded stimuli (*d* to *h*) obtained five of the six highest ratings, especially those elements with a sharp, coherent 3D interpretation (*d* and *f*). These elements contain Y-junctions, a common cue for three-dimensionality (Adelson, 2000). Continuous-shaded stimuli (*a* and *b*) occupy positions fourth and eighth, while stimulus *c* was rated as the penultimate one. As expected, stimuli with no 3D interpretation (*i* to *l*) were at four of the last five positions.

The contrast task shows a different scenario, as continuous-shaded stimuli (*a* to *c*) head the list for contrast reduction in test stimuli, followed by discrete-shaded stimuli (*d* to *h*) and, later but close, stimuli with no 3D interpretation (*i* to *l*). A linear mixed-model nested ANOVA yielded significant differences for the log contrast’s difference depending on the type of shading, $F(2, 62.535) = 38.741$; $p < 0.001$, and Bonferroni post hoc comparisons showed differences among continuous- and 3D discrete-shading (stimuli *a-c* vs. *d-h*; $p < 0.001$), continuous- and no-3D discrete-shading (*a-c* vs. *i-l*; $p < 0.001$), and for 3D and no-3D discrete-shading (*d-h* vs. *i-l*; $p = 0.032$). Furthermore, all stimuli yielded significant differences from 0 (all $p < 0.016$) but stimulus *k*, $t(13) = -0.293$, $p = 0.774$.

Figure 4 shows strong asymmetries in contrast perception for different shaded stimuli. In general, this asymmetry is not related with the perceived three-dimensionality but it seems to be related with the type of shading, being greater for continuous-shading stimuli. We will discuss the details of these results in the Discussion section.

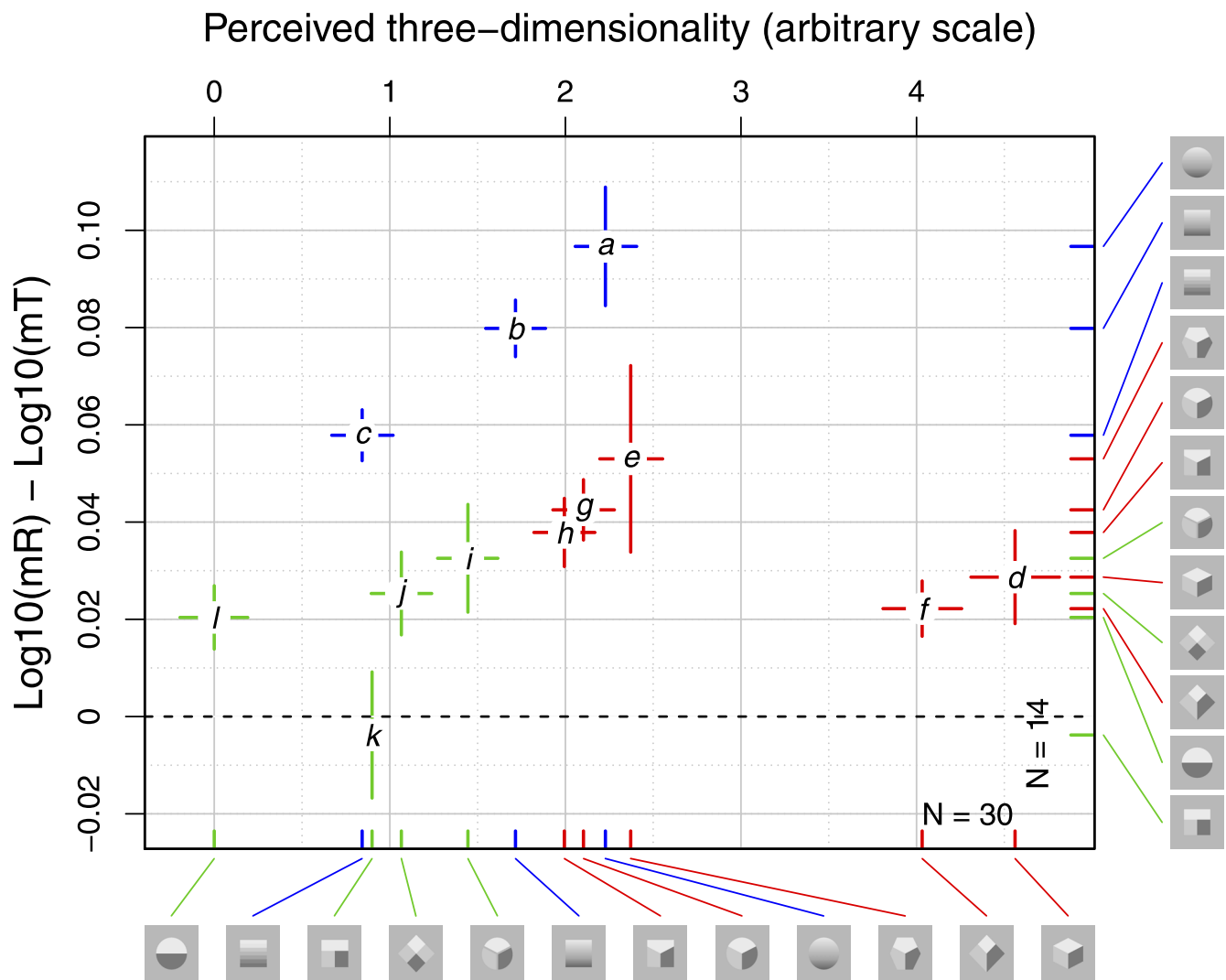


Figure 4. Letters represent conditions *a* to *k* with regard to the order task (horizontal axis; arbitrary scale) and difference of log contrasts (vertical axis), where positive values imply that test (top-dark) elements need lower contrast than the reference elements to be equated in perceived contrast. Vertical lines around the letters represent the standard error for log differences, while horizontal lines denote the 95% CI for ordering values. Scale for perceived 3D was anchored to the element *l*. Color signals different conditions as continuous shading elements (blue), discrete shading elements with 3D interpretation (red) and discrete patches without 3D interpretation (green).

Experiment 3: Perceived-contrast asymmetries and shading-orientation anisotropy

An aspect closely related to the interpretation of 3D shape from shading is the space position of the source of illumination, which determines the orientation of the changes in luminance. So, it is commonly known that the visual system assumes that light comes from above (Brewster, 1826; Rittenhouse, 1786), in the sense that stimuli with vertical shading have clearer and more stable 3D interpretations (with top-light circles perceived as bumps and top-dark ones as indentations).

On the other hand, horizontal shading generates weaker and unstable 3D perceptions (Ramachandran, 1988).

Some related findings are those about visual-search tasks, where vertically shaded stimuli render better detection rates than horizontally shaded stimuli. Nevertheless, that “preference” of the visual system for an “above” direction in search tasks must be defined with greater precision. Some studies (Mamassian & Goutcher, 2001; Sun & Perona, 1998; Symons et al., 2000) coincide in two aspects: first, the visual system can make effective discriminations in a wide range of orientations; second, this effectiveness increases when orientation tends to the vertical, but the maximum does not coincide with the vertical itself;

it stay some degrees left to the vertical, varying from around 25° to 45° .

Regarding the asymmetries in perceived contrast, Chacón (2004) showed that vertically shaded stimuli gave differences while horizontally shaded stimuli did not. If we assume that differences in perceived contrast are related to the orientation of shading and these perceived contrast differences can be used as a cue in visual search tasks (Chacón, 2004), then, we will expect that differences in perceived contrast will grow as the orientation of shading moves away the horizontal, showing a maximum bias toward the left of the vertical. We tested this hypothesis in Experiment 3.

Method

Participants

Nine observers (three males and six females), with normal or corrected-to-normal vision, participated voluntarily. Two subjects (JC and MC) were authors while the other seven were unaware of the purpose of the study.

Apparatus

The experimental set-up was the same as used in Experiment 1. Although, in this case, the monitor was held up in a rotary stand and rotated for the stimuli to show the desired orientation. Degaussing was made after each rotation.

Stimuli

The elements composing the stimuli were identical to those of Experiment 1 or to the element *a* in Experiment 2 (see top part of Figure 5), with stimuli built up filling out circles with a luminance ramp and Michelson contrast of 0.6. The only difference was that the monitor was rotated to obtain the orientations according to nine experimental conditions (-90° , -67.5° , -45° , -22.5° , 0° , 22.5° , 45° , 67.5° , 90°) where 0° corresponds to the vertical. This rotation prevents potential alterations due to sharp changes in the direction of the electrons' beam (García-Pérez & Peli, 2001; Naiman & Makous, 1992), which could invalidate the experiment. The elements were located inside the same 10-cell circular grid. Regardless of the orientation of the monitor, the imaginary line dividing both of halves were kept vertical with respect to the subjects.

Procedure

PSEs for the perceived contrast were measured using the same previous adaptive spatial 2AFC procedure used in Experiment 2. The subjects passed through nine

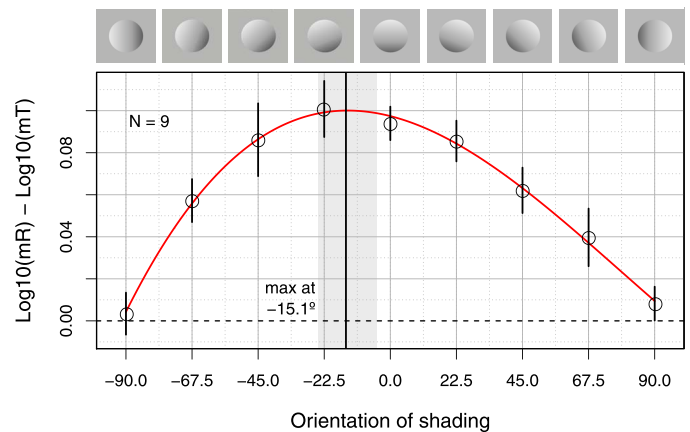


Figure 5. Differences in log contrast for nine participants in nine orientations. Vertical axis orientation corresponds to 0° (reference elements are shown upper). Circles show the mean \pm SE of nine subjects. The fitted third grade polynomial is plotted in red and its maximum is indicated with a vertical black line (at -15.1°). Gray region contains 95% CI for maximum, obtained from bootstrapping 2,000 samples.

consecutive sessions that consisted of one one-up/one-down staircase for each orientation, and the monitor was rotated after each condition. Presentation's order was determined and assigned randomly. Sessions lasted about 25 min.

Analysis and results

For each subject and condition, PSEs were obtained as in previous experiments. Then, the means for each condition were fitted to a third-grade polynomial model, with the form $\text{fit}(X) = 0.0089X^3 - 0.0367X^2 - 0.0203X + 0.09744$, where X is expressed in radians (see red line in Figure 5). Figure 5 shows the logarithmic differences in perceived contrast as a function of the stimulus orientation. It reveals how the differences get lower as the orientation becomes horizontal, with a maximum at the left of the vertical. The first derivative of the fitted function yields -15.1° (from the vertical) for maximum perceived contrast differences. t tests yielded means significantly greater than 0 ($p < .01$) for all the conditions except those of -90° ($p = 0.370$) and 90° ($p = 0.170$).

Experiment 4: Direction and selectivity of asymmetries in perceived contrast

In Experiment 1, 2, and 3 we have shown evidence of a strong asymmetry in contrast perception related to

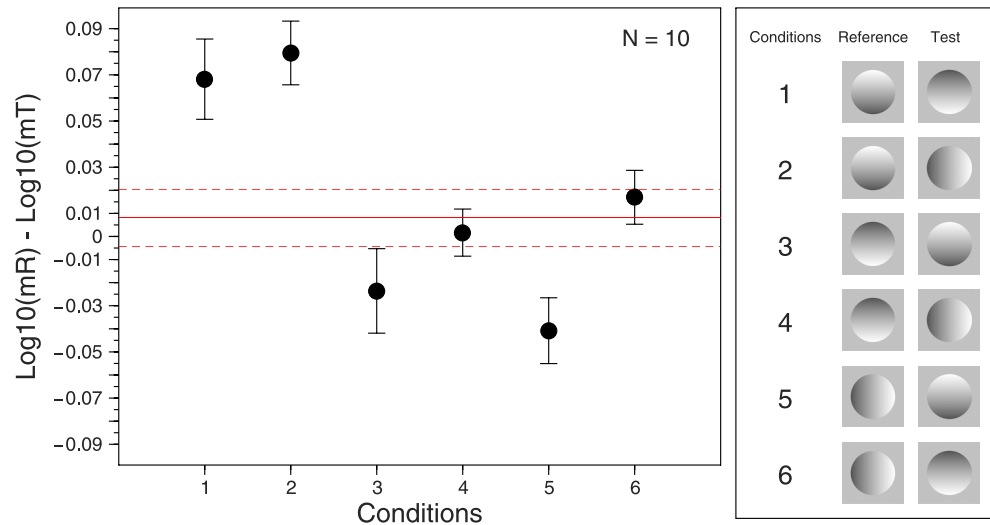


Figure 6. Mean differences in log contrast for equating perceived contrast. Each condition corresponds to comparisons between the contrast of the reference (fixed contrast, 50%) element and a particular test (see right panel). Zero value means that no perceived contrast difference was found between the reference and test. Positive values indicate that the contrast of the test stimulus was reduced to equate the perceived contrast of the reference one, while negative values indicate the opposite. Dots show the mean \pm SE for 10 subjects. Red line shows the mean results of the control experiment taking the three conditions together (top-light vs. top-light; top-dark vs. top-dark; and left-dark vs. left-dark). The dashed lines represent the 95% confidence interval. Right panel shows the elements of the tested conditions.

shaded stimuli. We also have assumed that shading perception has associated a reduced contrast for some (top-light) shaded objects. This assumption supports a more homogeneous perceived reflectance for convex objects in natural contexts (with an above-placed sun), which approximates to their true reflectance, so having apparent and ecological validity. However, our results only point to a *difference* in contrast, and no direction has been established for this effect. Thus, an explanation for the asymmetries found in Experiments 1, 2 and 3 may be that top-light shaded elements suffer a contrast reduction, but an alternative hypothesis is that top-dark elements suffer a contrast magnification.

Experiment 4 tests these hypotheses using the same experimental setup as in previous experiments, but making comparisons between different kinds of elements. To maximize the systematic variance, we chose those elements showing the highest asymmetries (top-light and top-dark shaded circles) to be compared with a stimulus showing no asymmetries: the horizontal shaded circle (left-dark), which shares the continuous shading and 3D interpretation.

Method

Participants

Ten observers (five males and five females), with normal or corrected-to-normal vision, participated voluntarily. One subject (ISP) was an author while the other nine subjects were unaware of the purpose of the

study. The experimental set-up was the same as in Experiment 1.

Apparatus

The distance, mean luminance, monitor, and the size of the elements, were the same as used in Experiment 1. For the experiment we used a Mac Pro 3.7 GHz (Apple, Inc., Cupertino, CA) Quad Core Intel Xeon E5 (graphics card AMD FirePro D300 2048 MB; Advanced Micro Devices, Inc., Sunnyvale, CA), running MATLAB R2009b (MathWorks) using the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997; www.psychtoolbox.org) and the Visual Stimulator DataPixx Lite (VPixx Technologies Inc., Montreal, Canada; www.vpixx.com) that gave us 14 bits of gray-scale resolution. The responses were recorded using ResponsePixx Handheld (VPixx Technologies). Gamma correction was performed using a Minolta LS-110 photometer (Konica Minolta Optics, Inc., Osaka, Japan).

Stimuli

We selected three elements from the previous experiments (see Figure 6), two vertically continuous-shaded circles (top-light and top-dark), and one horizontally continuous-shaded circle (left-dark, the element 90° of Experiment 3, see Figure 5) as control element. The elements were located inside the same 10-cell circular grid, with one type of elements on the left

side of the grid, and the other elements in the other half. Location of the elements was decided at random with equal probability for each trial. We tested six pair combinations of the three elements. For each pair, one element worked as reference (constant contrast) and the other as a test (variable contrast), giving a total of six experimental conditions (see Figure 6). To avoid ceiling effect, reference elements had 0.5 Michelson's contrast.

Procedure

PSEs for the perceived contrast were measured using the same previous adaptive spatial 2AFC procedure used in Experiment 2 and 3. We run 12 one-up/one-down staircases (two staircases per condition, 30 trials per staircase) that were distributed randomly in one single session lasting about 20 min. Previously, five out of 10 subjects performed a control experiment obtaining PSEs in three conditions comparing the same elements (top-light vs. top-light; top-dark vs. top-dark; and left-dark vs. left-dark).

Results

For each subject and condition, PSEs were obtained as in previous experiments. Figure 6 shows logarithmic difference between the contrast of the reference stimulus and the test stimulus as a function of the condition. Continuous red line shows the difference for the three conditions tested in the control experiment [$\log_{10}(0.5) - \log_{10}(0.4908)$; the averaged PSEs in log units was -0.309 , $SD = 0.024$; $n = 15$, five subjects \times three conditions]. Previous studies have shown that stimuli presented on the left visual field appear more intensely illuminated than the same stimuli presented on the right side (McCourt, Blakeslee, & Padmanabhan, 2013). Thus, we also tested the effect of the location in the visual field, left or right, of the reference stimulus on contrast perception. We re-analyzed the data of the control experiment selecting the trials where the reference was presented on the left and selecting the trials where the reference was presented on the right visual field. We did not find significant differences between the PSEs obtained in each location, paired t test, $t(14) = 0.525$, $p = 0.6$; the averaged PSEs in log units were Reference_{Left_visual_field} = -0.3039 , $SD = 0.061$, and Reference_{Right_visual_field} = -0.317 , $SD = 0.047$. Interestingly, when the reference stimuli were presented on the right side, the stimuli on the left side were perceived with slightly higher contrast in agreement with McCourt et al. (2013) findings; however, in our case this difference was not significant.

Results from conditions 1, 2, 3, and 5 show a clear contrast alteration. Note that this alteration is present when the top-light shaded circles are involved in the

comparisons. So, when acting as reference (conditions 1 and 2), the contrast of the test stimuli was reduced to match the perceived contrast. Complementarily, when the top-light shaded circles are working as test elements (conditions 3 and 5) their contrast was increased. Conditions 4 and 6 show no altered contrast perception. In summary, these results show that the perceived contrast of the top-light shaded stimuli is altered causing the asymmetry shown in Experiments 1, 2, and 3. In particular, these results are consistent with attenuation in the perceived contrast of the top-light shaded stimuli.

Discussion

In this research we have performed four experiments that show a consistent asymmetry in contrast perception related to shaded stimuli, replicating the results obtained previously (Chacón, 2004), and expanding them in several directions.

Experiment 1 generalizes the existence of differences in perceived contrast for various contrast levels, establishing it as a general effect not limited to specific contrast values. Furthermore, the linear trend of these differences, parallel to the equality line (with a slope of 1.03), suggests a consistent effect across contrast values.

Experiment 2 broadens the type of stimuli used to test this asymmetry and put this in relation to the degree of shading and the perceived three-dimensionality. In particular, Experiment 2 brings into question a line of thinking where shading *produces* 3D shape perception, which *produces* some other effects (as facilitating detection in search tasks, or reducing perceived luminance). Following this trend, some authors proposed that perceived three-dimensionality makes changes in the luminance pattern “due to shape,” so “its reflectance may be perceived as relatively constant” (Sun & Perona, 1996a, p. 165). This points to an elaborated, high order compensation mechanism that produces an effective reduction of contrast for that type of elements (i.e., top-light elements). Following this reasoning, three-dimensional perception will be impaired or inexistent for stimuli under an “unusual point of view” (i.e., top-dark elements), so contrast reduction will not take place, and therefore, the asymmetries will be produced by an orientation-selective mechanism.

Our Experiment 2 enquired the proposal that the perceived 3D shape *produces* a perceived contrast asymmetry. Figure 4 shows, at first sight, that no apparent relation exists between subjective 3D ordering and differences in perceived contrast. A closer inspection reveals some regularity, but related to the patterns

of luminance distribution. For instance, continuous-shaded elements (*a* to *c*, in blue) show the greatest asymmetries in perceived contrast but occupy middle and low positions in the 3D ordering rank. Discrete-shaded elements (*d* to *h*) show homogeneous middle values of alterations in perceived contrast, while they take five of the six highest positions in 3D-shape perception. Finally, elements with no 3D interpretation (*i* to *l*) occupy lower positions both in ordering and contrasts asymmetries. Previously, (Previc & Naegele, 2001) measured perceived 3D for similar stimuli and they also did not find correlation with processing times found in search experiments (Sun & Perona, 1996b).

Once the relation between 3D perception and perceived contrast is discarded, we can study the relations between the type of luminance distribution and perceived contrast. Figure 4 has got, on its right side, the elements sorted by differences in perceived contrast. A first sight shows an almost perfect ordering in relation to the type of luminance distribution. Elements *a* and *b*, which share a continuous-change luminance pattern, show a large alteration of perceived contrast between reference and test elements. Element *c*, (included in continuous shading but) deliberately located in a middle position between continuous and discrete shading, shows such a middle behavior with respect to the asymmetries in perceived contrast. The following cluster includes all the discrete-shaded elements (*d* to *h*) but, also, elements *i* and *j*. The 3D interpretable elements produce an asymmetry in perceived contrast lower than that for continuous-shaded elements, and more homogeneous. All these elements share a Y-shaped luminance distribution, a classical cue to three-dimensionality (Adelson, 2000). It is interesting to note that, despite their high (and variable) 3D valuation, their associated contrast asymmetries are very homogeneous, as if they were activating exactly the same mechanism; a mechanism that, furthermore, seems independent of the details. This may be the reason for the contrast alteration in element *i* (broken pie) and, to a lesser extent, for element *j*, which shows an X-shaped luminance distribution (usually associated to changes in reflectance or transparency; see Adelson, 2000).

Element *k* was the only one not showing significant differences from 0, and shows a T-shape pattern not interpretable as 3D shape. Element *l* serves as a control to differentiate shading effect (element *a*) from a simple polarity effect. Although there is evidence suggesting that these two elements (*a* and *l*) are processed by different mechanisms (Humphrey et al., 1997; Symons et al., 2000), it has also been found that bipartite disks show similar but lower contrast asymmetries than shaded disks in search tasks (Aks & Enns, 1992; Kleffner & Ramachandran, 1992), what can indicate (as here) a suboptimal stimulation.

At this point, it is important to note that continuous-shaded elements have a very low proportion of their surface containing extreme luminance values, as they are limited to the end sides of the patch. This is especially true for shaded discs, as they have only a few pixels with highest and lowest luminances. Discrete elements, in turn, contain a greater proportion of extreme luminance values (usually two-thirds of the total area), while suffering a lesser distortion. This separation between continuous and discrete distributions of luminance resembles some experimental findings about reflectance perception. For instance, the classical effect in the wall-of-blocks pattern from Adelson (1993; figure 2) was surpassed by Logvinenko (1999; figure 5b) when substituted the rectangular transparent “stripes” by a continuous, smooth transparent sinusoidal layer. In these cases, and in ours, similar mechanisms (if not the same) compute a transformation that we can name “correction,” stronger for continuous luminance changes than for discrete ones.

Summing up Experiment 2, we found that the differences in contrast perception for continuous and discrete shading suggest two possible mechanisms, each specialized in a type of luminance distributions (coincident with smooth and discrete shading), with different strength (greater for continuous shading) and sharing a similar effect or “goal”: to reduce the contrast (so approximating to the real reflectance of the object). Specifically, we assume that this contrast reduction is carried on the reference (top-light) elements, while contrast for tests elements (top-dark) remains unaltered.

Under this suggestion, the chain composed by shading, 3D-shape and contrast-reduction (Sun & Perona, 1996a) may be substituted by a first node (shading-pattern) followed by two parallel links: 3D-shape perception and contrast reduction. In reference to contrast reduction, the involved mechanisms seems to be a sort of *quick-and-dirty* one (very quick, spatially parallel, and ecologically relevant; see Aks & Enns, 1992), that agrees with the idea of very primitive “modules” linked to shading processing (Symons et al., 2000, p. 567). This became reinforced by the fact that asymmetries for elements *i* and *j* are similar to those of 3D interpretable elements. There is no way to extract 3D information from them, but it seems that their patterns are similar enough to 3D patterns to activate the mechanism involved. This could be in line with a basic mechanism based more on rough distributions of luminance than on elaborated rules/procedures derived from a detailed analysis of the three-dimensionality cues. In short, this mechanism seems to work only on (a) top-light, and (b) continuous or discrete (Y-shaped) luminance distributions, having stronger effects for continuous luminance changes. These findings reinforce

Chacón's (2004) suggestion that this contrast mechanism could be responsible for the asymmetries found in search tasks. So, the characteristic that produces the asymmetries in these search experiments could not be the 3D shape, but merely the higher perceived contrast—not corrected—for some stimuli.

In Experiment 2 we explored the main area of interest about shading: the relation between shading and the perceived shape of objects. In Experiment 3 we explored the second area of interest: the influence of the source of illumination and, in particular, the assumed direction (orientation) of the light source. The assumption of a light source located above the observer, and what exactly means “above” has been studied mainly by means of search and 3D-rating tasks, which means that the preferred location is that with a better detection rate or a higher 3D rate (Gerardin et al., 2007; Mamassian & Goutcher, 2001; Sun & Perona, 1998; Symons et al., 2000). Results from Experiment 3 show a strong parallelism to those obtained in search and 3D rating tasks with shaded stimuli, which suggest that: (a) differences in perceived contrast are smoothly reduced as shading orientation varies from vertical to horizontal; (b) the highest differences in perceived contrast—as in visual-search asymmetries—do not occur for strictly vertical gradients, but for gradients whose orientation is displaced to the left (see Figure 5).

Finally, Experiment 4 tested the idea, generally accepted but unproved, that there is a contrast reduction for the reference (top-light) elements, against the possibility of a contrast magnification for tests elements (top-dark). To test this, we used three shaded circles, top-light, top-dark, and one element showing no asymmetries from Experiment 3 (left-dark). We tested six possible combinations (see Figure 6) and our results were conclusive: In all conditions where the top-light stimulus (see Figure 6, conditions 1, 2, 3, and 5) was the reference or the test element, the results are consistent with an attenuation in the perceived contrast of the top-light vertically-shaded stimuli. Results of conditions 4 and 6 (Figure 6) show that left-dark and top-dark stimuli were perceived with similar contrast. Previous findings, using 3D cubes presented in a stereo display, have found that arrays of top-dark cubes are perceived more intensely illuminated (higher brightness) than arrays of top-light cubes (McCourt et al., 2013). McCourt et al. (2013) suggested that top-dark objects are perceived with higher contrast as a consequence of this increased perceived illumination and also because top-dark stimulus could be interpreted as a convex stimulus illuminated from below. However, our results from Experiment 4 show that top-dark stimuli are perceived with higher contrast than top-light stimuli because there is an attenuation in the perceived contrast of the top-light stimuli while the

perceived contrast in the top-dark (left-dark) stimuli was unaffected.

As with visual illusions, it seems reasonable to think that we assist to the use of a selective mechanism (for contrast reduction) that can offer an advantage in object recognizing, but yields an anomalous result under certain configurations. From this perspective, we can answer to Kleffner and Ramachandran (1992, p. 27), when found “surprising and counterintuitive” the fact that it is easier to find an indentation among protuberances than the inverse, especially from an evolutionary perspective. The question is not what special characteristic has the indentations to be more easily detected, but what special characteristic does not have the indentations, which makes them more easily detected.

Keywords: shaded stimuli, perceived contrast, contrast asymmetries, shape from shading

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Corresponding authors: Ignacio Serrano-Pedraza; José Chacón.

Email: iserrano@ucm.es; jchacon@ucm.es.

Address: Faculty of Psychology, Complutense University of Madrid, Spain.

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