Vision Res. Author manuscript; available in PMC 2013 May 01.

Published in final edited form as:
Vision Res. 2012 May 1; 60C: 40–50. doi:10.1016/j.visres.2012.03.006.

When is spatial filtering enough? Investigation of brightness and lightness perception in stimuli containing a visible illumination component

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Abstract

Brightness (perceived intensity) and lightness (perceived reflectance) matching were investigated in seven well-known visual stimuli that contain a visible shadow or transparent overlay. These stimuli are frequently upheld as evidence that low-level spatial filtering is inadequate to explain brightness/lightness illusions and that additional mid- or high-level mechanisms are required. The argument in favor of rejecting low-level spatial filtering explanations has been founded on the erroneous assumption that equating test patch and near surround luminance is sufficient to control for and rule out this type of mechanism. We tested this idea by comparing the matching behavior of four observers to the predictions of the ODOG multiscale filtering model (Blakeslee & McCourt, 1999). Lightness and brightness matching differed significantly only when test patches appeared in shadow or beneath a transparency. Lightness and brightness matches were both significantly larger under these conditions; however, the lightness matches greatly exceeded the brightness matches. Lightness matches were greater for test patches in shadow or beneath a transparency because lightness matches under these conditions were based on inferential (not sensory-level) judgments where observers attempted to discount the difference in illumination. The ODOG model accounted for approximately 80% of the total variance in the brightness matches (as well as in the lightness matches for targets not in shadow or beneath a transparency), and successfully predicted the relative magnitude of these matches in five of the seven stimulus sets. These results indicate that multiscale spatial filtering provides a unified and parsimonious explanation for brightness perception in these stimuli and imply that higher-level mechanisms are not required to explain them. The model was not as successful for the Argyle and Wall of Blocks illusions in that it incorrectly rank-ordered the relative magnitude of the effects across different versions of the stimuli. It is an important question whether such model failures are due to known but corrigible limitations of the ODOG model or whether they will require other (possibly higher-level) explanations.

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The contents of this report are solely the responsibility of the authors and do not necessarily reflect the official views of the NIH, NCRR, NIGMS or NEI.
Commercial relationships: none.

INTRODUCTION

A central question in the study of visual perception is how and under what circumstances the visual system is able to separate the physically invariant reflectance of a surface from its potentially changing illumination. The intensity distribution falling on the photoreceptor array is the product of these two sources and their independent recovery is thus an ill-posed problem in that there are myriad combinations of illumination and reflectance that can give rise to any particular intensity distribution, and in the absence of additional information there is no way to uniquely recover the physically correct solution. Much of the current debate surrounding brightness (perceived intensity) and lightness (perceived reflectance) perception, therefore, centers on the nature of the prior assumptions and processing strategies the visual system uses to parse (correctly or incorrectly) the intensity distribution at the retina into components of surface reflectance and illumination. Perceptual illusions have historically been and continue to be informative in this regard because of their potential to reveal these underlying processing mechanisms.

Here we investigate brightness (perceived intensity) and lightness (perceived reflectance) matching in seven well-known visual stimuli that contain a visible illumination component (i.e., a shadow or transparent overlay). The stimuli appear in Figs. 1–7 and include: 1) the Williams, McCoy and Purves (1998) version of the shadow simultaneous brightness/ lightness contrast illusion (Gilchrist, Delman, & Jacobsen, 1983); Purves, Williams, Nundy, & Lotto, 2004); 2) the snake illusion (Somers & Adelson, 1997; Adelson, 2000); 3) a paint/ transparency/shadow checkerboard illusion derived from Adelson’s checkershadow illusion (Adelson, 1995); 4) the paint/shadow illusion (Hillis & Brainard, 2007); 5) the argyle Illusion (Adelson, 1993); 6) the wall of blocks illusion (Adelson, 1993; Logvinenko, 1999); and 7) a Cartier-Bresson photograph of a natural scene (similar to one used by Gilchrist, 2006).

These stimuli have been frequently upheld as evidence that low-level spatial filtering explanations are inadequate to explain brightness/lightness illusions (and by implication brightness perception more generally) and that additional or alternative mechanisms are required which depend on a variety of factors such as mid-level junction analysis (Adelson, 2000); Gestalt grouping (Gilchrist, 2006); knowledge of image statistics learned through goaldirected behavior (Purves et al., 2004); or parsing of the visual scene into components of reflectance and illumination (Logvinenko & Ross, 2005; Gilchrist, et al.,1983; but see Blakeslee, et al., 2008 for an alternative explanation of these results). The argument in favor of rejecting low-level spatial filtering explanations has been founded on the erroneous assumption that equating test patch and near surround luminance is sufficient to control for and rule out this type of mechanism. This assumption might be valid if spatial filtering were performed solely by small receptive field "edge-detectors"; however, it is now well established both psychophysically (Campbell & Robson, 1968; Pantle & Sekuler, 1968; Blakemore & Campbell, 1969; Wilson, McFarland, & Phillips, 1983; Phillips & Wilson, 1984; Hess, 2003) and physiologically (DeValois, Albrecht & Thorell, 1982; DeValois & DeValois, 1988; Wilson & Wilkinson, 2003) that the visual system is comprised of multiple filter channels tuned to different spatial frequencies and orientations. This means that regions of the surround remote from the test patches can influence test patch brightness/ lightness due to multiscale spatial filtering and that holding local luminance constant is *not* adequate as a control to justify the rejection of low-level filtering explanations (Kingdom, 2003; Blakeslee & McCourt, 2003; 2005; Kingdom, 2011).

Although local luminances remain essentially unchanged in the illusory stimuli under investigation, the larger context within which the identical targets are embedded does not. This is clearly illustrated by examining the Control stimulus (which appears homogeneously illuminated) and the Experimental stimulus (which appears to contain an illumination discontinuity) of the shadowed simultaneous brightness/lightness contrast display (Gilchrist et al., 1983; Williams et al., 1998; Purves et al., 2004). The Control stimulus (Fig. 1, lower left) demonstrates the classic simultaneous brightness/lightness contrast effect in which a gray test patch on a low luminance background appears brighter/lighter than an identical test patch on a high luminance background. In the Experimental stimulus (Fig. 1, lower right) the test patches and near backgrounds are identical to those in the Control stimulus; however, a dark far surround has been added that causes the left half of the stimulus to appear to be in shadow. This makes it unclear whether the larger brightness/lightness difference perceived in this Experimental stimulus results from the added far surround exerting a non-local effect through spatial filtering (Kingdom, 2003; 2011; Blakeslee & McCourt, 2003; 2005; Todorovic, 2006) or whether additional mechanisms are required (Adelson, 2000; Purves et al., 2004; Gilchrist, 2006; Logvinenko & Ross, 2005). The situation in the snake illusion (Somers & Adelson, 1997; Adelson, 2000) is very similar. The test patches in the Control (Fig. 2, lower left) and Experimental (Fig. 2, lower right) stimuli share the same luminance. In addition, the upper test patches in both stimuli have the same lower background luminance and the lower test patches share the same higher background luminance. The Experimental snake stimulus differs from the Control, however, in the luminances of more distant regions (the snake undulations) that cause the upper test patch to appear to lie beneath a transparent overlay. Again, it is unclear whether the larger brightness/lightness difference observed between the test patches in the Experimental stimulus is attributable to low-level spatial filtering (Todorovic, 2006; Kingdom, 2011) or to additional mid-level (Adelson, 2000) or high-level mechanisms (Logvinenko & Ross, 2006). The same confound occurs in each of the other illusory stimuli as well. In the three stimulus conditions of the paint/transparency/shadow illusion derived from Adelson’s checkershadow illusion (Adelson, 1995) (Fig. 3) the checks that serve as test patches (marked by asterisks) are identical in luminance and are each immediately surrounded by checks of the same luminances. The differences in the distribution of luminances at the edges of the region containing the darkest checks, however, results in the perception that illumination is either homogeneous (Fig. 3, lower left), or that it is not homogeneous due to a transparent overlay (Fig. 3, lower middle) or a shadow (Fig. 3, lower right). The paint and shadow conditions of the paint/shadow illusion (Hillis & Brainard, 2007) (Fig. 4) can be described in exactly the same manner. Here, however, test patches of identical luminance have been superimposed on the checks in each region. Again, in the rather complex patterns of luminance making up the argyle (Adelson, 1993) (Fig. 5) and wall of blocks illusions (Adelson, 1993; Logvinenko, 1999; Logvinenko & Ross, 2005) (Fig. 6) the Experimental stimuli (Fig. 5, lower left panel; Fig. 6, lower left panel and lower right panel) differ from the Control stimuli (Fig. 5, lower right panel; Fig. 6, two middle panels) to produce the perception of a transparent overlay or shadow.

We assess the degree to which multiscale spatial filtering suffices to explain brightness/lightness perception in the above illusions and in the Cartier-Bresson photograph by comparing observer brightness (perceived intensity) and lightness (perceived reflectance) matches at test locations within these stimuli with the predictions of the ODOG model of Blakeslee and McCourt (1999). The defining features of the ODOG model (Fig. 8) are characteristics exhibited at early stages of cortical visual processing, e.g., spatial frequency selectivity, orientation selectivity, and contrast gain control. The ODOG model has been shown to successfully account for a large body of quantitative data and simultaneously explains a large number of seemingly diverse phenomena using a single set of parameter values (Blakeslee & McCourt, 1999, 2001, 2003, 2004; Blakeslee, Pasieka & McCourt, 2005; Blakeslee, Reetz & McCourt, 2009).

METHODS

Two of the authors (BB and MM) and two naïve observers (KM and LL) participated in the experiments. All observers possessed normal or corrected-to-normal vision. Each participant provided informed consent and the experimental protocol was approved by the NDSU IRB.

Stimuli were presented on a 22” Mitsubishi DiamondPro (model 2070) CRT display at a frame refresh rate of 85 Hz. Stimuli were displayed using Presentation (Neurobehavioral Systems, Inc.). Stimuli were presented as pseudo-grayscale images possessing 1000 linear intensity steps using the bit-stealing method of Tyler, Chan, Liu, McBride, and Kontsevich (1992). Gamma correction was accomplished via look-up tables following photometric calibration (ColorCAL, Cambridge Research Systems). Display format was 1024 (w) × 768 (h) pixels. Viewing distance was 57 cm, resulting in a stimulus field measuring 40° in width by 30° in height. Individual pixels measured 0.039° × 0.039°. Maximum display luminance was 107 cd/m^2.

Test stimuli occupied the upper two thirds of the display. Square matching patches were presented on checkerboard backgrounds (check contrast 30%) centered in the lower third of the display. The size of the square matching patch and background were scaled for each stimulus to make the matching patch the same size as the stimulus test patch (0.78°, 0.94°, 1.09°, 1.40° or 1.56°). The checkerboard background, therefore, was always nine times larger than the matching patch and the matching patch was always 16 times larger than the individual checks of the background. The horizontal position of the test patch to be matched on any given trial was indicated by a narrow (1 pixel wide) line that served as a pointer. This line was of low contrast and located several degrees below the stimulus. Where the vertical position of the test patch was ambiguous, an additional line pointer located to the far right of the stimulus specified the test patch location. Within a block of trials observers were instructed to match either the brightness (perceived intensity) or the lightness (perceived reflectance) of the test patch. To avoid any confusion observers were instructed that brightness matching required them to “adjust the matching patch to match the intensity or amount of light coming from the test patch ignoring, as much as possible, other areas of the display”. Lightness matching instructions were to “adjust the matching patch to look as if it is cut from the same piece of paper as the test patch and consider the illumination conditions in the display”. Observers made 10 matches per condition in each of these two blocks, for a total of 20 match settings at each test patch location. On each matching trial the initial luminance of the matching patch was randomized. Observers controlled subsequent increments or decrements in matching patch luminance via button presses. Each button press caused a luminance change of 1% relative to the maximum luminance (107 cd/m^2).

RESULTS

The bar graphs in the upper panels of Figures 1–7 plot the grand mean of the four observers’ mean brightness and lightness matches for each test patch within the various stimulus displays. The error bars depict 95% confidence intervals. A three-way within-subjects ANOVA with Task Type (Brightness versus Lightness), Stimulus Type (Experimental versus Control) and Patch Location (Higher Luminance Background versus Lower Luminance Background) as independent variables was performed on the matching data for each of the six illusion displays. Note that since it lacked a Control condition, the Cartier-Bresson stimulus was analyzed separately using a two-way within-subjects ANOVA where Task Type and Patch Location were independent variables. The source of each significant interaction was traced using appropriate post-hoc tests (i.e., two-way ANOVAs, one-way ANOVAs and/or paired comparisons).

The findings are consistent across all stimuli (see Supplementary Data Tables 1–7) and exhibit three main effects that are readily observable. First, there is a consistent ***main effect of Task Type***, where Lightness settings (i.e., matches to perceived reflectance, depicted by the white bars) are significantly higher than Brightness settings (i.e., matches to perceived intensity, depicted by gray bars). The source of this effect is that Lightness matches are higher than Brightness matches for test patches located in shadow or under a transparent overlay (see locations labeled: Fig. 1, ShadowSBCL; Fig. 2, ESnakeL; Fig. 3, TransR & ShadowR; Fig. 4, CheckR & TestR; Fig. 5, ArgyleL; Fig. 6, OrigRow2 & BlurRow2; and Fig. 7, TF2, TF3, TF6, BK2 & BK6. For the same reason there is also a consistent ***main effect of Stimulus Type*** where both Lightness and Brightness settings are significantly higher in Experimental versus Control Stimulus Types since only the Experimental Type displays contain test patches located in shadow or under a transparency. These results are consistent with previous studies (Arend & Spehar, 1993; Blakeslee, et al., 2008) showing that lightness is dissociable from both brightness and brightness contrast when illumination discontinuities are visible and allow subjects to make inferential/projective (Reeves, Amano & Foster, 2008) judgments of lightness (i.e., to discount the shadow or transparency in judging lightness). Although Lightness and Brightness settings are both higher in these Experimental Type displays, the Lightness settings are significantly greater than the Brightness settings (see pairwise comparisons: green bars in Figs. 2–8). Third, there is a consistent ***main effect of Patch Location*** illustrating the classic simultaneous brightness/ lightness contrast effect. Brightness and Lightness settings for patches situated in regions of relatively low luminance are significantly higher than settings for patches situated in regions of relatively high luminance.

In addition, there are three significant two-way interactions. First, there is a consistent ***Task Type × Stimulus Type interaction*** that occurs because the effect of Stimulus Type (Experimental versus Control) is significantly greater for Lightness settings when test patches are situated in shadow or under a transparency, i.e., in Experimental Type displays. Second, there is a consistent ***Task Type × Patch Location interaction,*** where the influence of patch location is significantly greater for Lightness settings, since some Patch Locations in Experimental Type displays are in shadow or under a transparency where Lightness settings are significantly higher than Brightness settings. Third, there is a consistent ***Stimulus Type × Patch Location interaction,*** where the influence of Patch Location is significantly greater in Experimental versus Control Type displays where some Patch Locations in the Experimental Type displays are in shadow or under a transparency. As discussed previously, both Lightness and Brightness matches are greater for these Patch Locations, however, the Lightness matches greatly exceed the Brightness matches. Finally there is a consistent three-way interaction of ***Task Type × Stimulus Type × Patch Location*** because the magnitude of the Stimulus Type × Patch Location interaction is significantly larger for Lightness than for Brightness settings.

In order to more closely analyze the brightness (perceived intensity) effects associated with all but the Cartier-Bresson photograph, a two-way within-subjects ANOVA was performed on the brightness matching data alone with Stimulus Type (Experimental versus Control) and Patch Location (Higher Luminance Background versus Lower Luminance Background) as independent variables (see Supplementary Data Tables 1–6). The source of each significant interaction was traced using appropriate post-hoc testing (i.e., one-way ANOVA and/or paired comparisons). The findings are consistent across all six stimulus sets and show two main effects which can be observed by examining the gray bars in Figures 1–6. First, there is a consistent ***main effect of Stimulus Type***. Brightness matches are significantly higher for Experimental versus Control Type displays because in the Experimental displays some of the test patches are in shadow or under a transparency and Brightness matches are higher under these conditions. Second, there is a consistent ***main effect of Patch Location.***

Brightness settings for patches situated in regions of relatively low luminance are significantly higher than settings for patches situated in regions of relatively high luminance i.e., the classic simultaneous brightness contrast effect. Finally, there is a consistent ***Stimulus Type* × *Patch Location interaction***. The influence of Patch Location is significantly greater in Experimental versus Control Stimulus Types where some Patch Locations in the Experimental Type displays are in shadow or under a transparency and Brightness matches are greater in these Patch Locations. Significant Holm-Bonferroni-corrected (Holm, 1979) pair-wise comparisons are indicated in Figures 1–6 by red bars.

MODELING

To test the hypothesis that the observed effects can be accounted for by multiscale spatial filtering and do not require additional mechanisms, we compared the lightness and brightness matches to the predictions of the ODOG multiscale filtering model (Blakeslee & McCourt, 1999). Model output was scaled to the brightness data set as a whole and not to individual illusions. ODOG model predictions are illustrated by the filled circles in Figures 1–7. The model was judged to be successful if it correctly predicted the direction and approximate magnitude of test patch brightness (or lightness) differences within individual stimuli, as well as the rank order of these differences between Experimental and Control versions of each stimulus. Using this criterion the ODOG model successfully predicted the brightness of the test patches (as well as the lightness matches under homogeneous illumination) in: 1) the shadow simultaneous brightness contrast illusion (Gilchrist et al., 1983; Williams, et al., 1998; Purves et al., 2004); 2) the snake illusion (Somers & Adelson, 1997; Adelson, 2000); 3) the paint/transparency/shadow checkerboard illusion (derived from Adelson, 1995); 4) the paint/shadow illusion (Hillis & Brainard, 2007); and 5) the Cartier-Bresson photograph (similar to one used by Gilchrist, 2006). Note that the ODOG model slightly under-predicted the brightness of some test patches situated in shadow or under a transparency (i.e., see Fig. 3, TransR and ShadowR and Fig. 4, ShadowCheckR and ShadowTestR). While these discrepancies are relatively small they are nevertheless intriguing since it has been previously shown that in the presence of a visible illumination component test patch brightness appears to be drawn slightly in the direction of its associated lightness (Adelson, 1993; Kingdom, et al., 1997). The model is less successful in predicting the brightness matches (and the lightness matches under homogeneous illumination) for the Argyle and Wall of Blocks illusions. Although the model correctly predicted the direction of the brightness differences within each individual stimulus (Experimental and Control), it under-predicted the magnitude of these test patch brightness differences and failed to correctly rank order the size of the brightness differences across: 1) the original Argyle and its Control (Adelson, 1993); 2) the original Wall of Blocks and its Control (Adelson, 1993), and the original Wall of Blocks, the blurred illumination version (Logvinenko, 1999) and a split condition Control (Logvinenko & Ross, 2005). Figure 9 plots all of the brightness matches (circles), as well as the lightness matches from the conditions that did not contain a shadow or transparent overlay (diamonds) against ODOG model predictions for these same stimuli. Despite the discussed under-predictions and failures, overall the ODOG model accounts for a significant proportion ($R^2 = 0.826$; black line) of the total variance in the brightness matches (Brightness Match = .105*(ODOG Model Output) + 31.0; $F_{1,42} = 199.38$, $p < 0.001$) and in the lightness matches ($R^2 = 0.787$; gray line) made in the absence of a visible illumination component (Lightness Match = .111*(ODOG Model Output) + 29.6; $F_{1,28} = 103.19$, $p < 0.001$).

DISCUSSION

The significant main effects and interactions associated with the lightness (perceived reflectance) and brightness (perceived intensity) matching behavior indicate that while the two types of judgments are not significantly different under homogeneous illumination, they differ markedly when the illumination is interpreted to be nonhomogeneous, i.e., when one of the test patches is seen beneath a transparent overlay or in shadow (see green comparison bars in Figures 1–7). Under these conditions subjects are able to make inferential (Blakeslee & McCourt, 2003a, b; Blakeslee et al., 2008) or projective (Reeves, Amano & Foster, 2008) judgments of lightness (i.e., to discount the shadow or transparency to estimate the reflectance of the underlying surface). This finding is consistent with previous studies (Arend & Spehar 1993 a; b; Blakeslee, et al., 2008) showing that under stimulus conditions where there is a visible illumination component it is possible to demonstrate three independent dimensions of achromatic experience: brightness (perceived intensity), brightness-contrast (perceived local intensity difference), and lightness (perceived reflectance). In the absence of a visible illumination component, however, achromatic visual experience reduces to two dimensions and, depending on stimulus conditions and observer instructions, lightness judgments are identical to either brightness judgments or to brightness-contrast judgments (Arend & Spehar, 1993 a; b).

Inferred- (Blakeslee & McCourt, 2003 a; b) or projective- (Reeves, et al., 2008) lightness judgments require the subject to deliberately take account of the illuminant in order to deduce the reflectance of the underlying surface. Under some circumstances this type of lightness judgment can be relatively effortless and accurate, for example where a shadow or transparent overlay falls across only a portion of an object or surface, allowing its lightness (perceived reflectance) to be judged based on parts of the object or surface lying outside of the shadow or transparency. This strategy for judging inferred-lightness is probably a highly overlearned behavior and is illustrated in Fig. 7, for the area labeled BK2, where observers were asked to match the lightness (perceived reflectance) of a shadowed part of the wall, but where a part of the same wall not in shadow is also clearly visible. Note that the variability of the mean lightness matches across observers for area BK2, as indicated by the error bars, is comparable to that for brightness matching. Adelson’s (1993; 2000) checker-block stimulus provides another well-known example of this type of stimulus situation. Under other conditions where an object or surface is completely shadowed or under a transparent overlay, and where its illumination must be estimated (and discounted) based entirely on the intensities of other nonadjacent image regions, however, inferential lightness judgments are effortful and imprecise. This is illustrated in Fig. 7 where observers were asked to match the lightness (perceived reflectance) of the shadowed test fields labeled TF2, TF3, and TF6. The variability of lightness matches across observers in this condition is much greater than for BK2. Note that although not illustrated in the figures the within-subjects variability of the inferred-lightness matches mirrored these between subject results.

It is important to stress that the deliberate judgments of inferred-lightness, made possible by a visible illumination component, are very different from the sensory-level judgments of lightness (which do not differ from brightness judgments) made when illumination is homogeneous. In addition, studies of stimuli like those in the present experiment have almost always (but see Blakeslee, et al., 2008) been interested in the sensory-level brightness illusions and brightness (perceived intensity) has been deliberately measured. Confusingly, however, these same studies discuss these illusions in terms of lightness (Hillis & Brainard, 2007; Adelson, 2000; Logvinenko & Ross; 2005; Gilchrist, 2006; Todorovic, 2006; Kingdom, 2011). The lack of appreciation that these sensory-level “lightness” judgments are also identical to brightness judgments (and are actually a misnomer since inferred-lightness judgments are also possible in these situations) may persist in part because it has only rarely been the case that both lightness and brightness are measured in the same experiment (Schirillo, Reeves, & Arend, 1990; Arend & Spehar, 1993 a, b; Blakeslee, et al., 2008).

The above observations suggest that the visual system judges lightness (perceived reflectance), to which it has no direct access, based on the best information available. Under homogeneous illumination brightness and lightness are perfectly correlated and judging lightness based on brightness is the optimal strategy. When illumination varies, however, this correspondence breaks down and judgments of reflectance are more accurately based on either brightness contrast (i.e., when scene illumination varies over time but not space, that is, remains homogeneous) or on an inferential judgment of reflectance (when illumination varies over space). Note, that employing the optimal strategy to judge reflectance depends on the observer having some knowledge of the stimulus situation (i.e., whether illumination is homogeneous, spatially homogeneous but varying over time, or spatially nonhomogeneous). Although it is clear that observers are capable of making these judgments when instructed to do so under laboratory conditions it is unclear to what extent the best strategies are employed in normal viewing. This is especially true under the more difficult conditions discussed above where illumination is visibly nonhomogeneous and the surface is completely within a shadow or beneath a transparency. Under these circumstances it may well be the case that when asked to judge lightness (perceived reflectance) observers, without clear instruction to take the illumination conditions into account, resort to a simpler and more direct sensory-level judgment of brightness. Understanding that lightness judgments may be based on any one of three different dimensions, and possibly not even the optimal dimension for a given stimulus condition, is crucial to unraveling the literature and to advancing understanding of brightness and lightness perception.

The significant main effects and interactions associated with the analysis of the brightness matching data alone can be understood as due to two factors. The first, as expected, is the classic simultaneous brightness contrast effect, i.e., Brightness settings for patches situated in regions of relatively low luminance are significantly higher than settings for patches situated in regions of relatively high luminance. In addition, however, Brightness matches in some instances were found to be significantly higher for Experimental versus Control Stimulus Types, where in the former condition test patches appeared in shadow or under a transparency. As noted earlier, these are also the only conditions under which Lightness and Brightness are dissociable and where Lightness settings exceed Brightness settings. The ODOG model (Blakeslee & McCourt, 1999) correctly predicted the direction and approximate magnitude of test patch brightness differences within five of the seven stimulus sets (Figs. 1– 5) as well as the rank order of these brightness differences between the Experimental and Control versions of each stimulus (Figs. 1– 4). Importantly, it predicted the higher brightness (perceived intensity) matches for test patches situated in shadow or under a transparency in the shadow simultaneous brightness contrast illusion, the snake illusion, the paint/transparency/shadow checkerboard illusion, and the paint/shadow illusion, although it slightly under-predicted the magnitude of this brightness effect for the paint/transparency/shadow and paint/shadow stimuli. These findings indicate that low-level multiscale spatial filtering can provide a unified and parsimonious explanation and that higher-level mechanisms are not required to explain the brightness effects (or lightness effects for test patches not in shadow or beneath a transparency). In addition, these results underscore that controlling for local luminance differences is not adequate to rule out low-level spatial filtering as an explanatory mechanism. Interestingly, the model was not as successful for the Argyle and Wall of Blocks illusions, where although it correctly predicted the direction of the brightness effects, it under-predicted the magnitude of the test patch brightness differences and incorrectly rank ordered the relative magnitude of the effects across different versions of the stimuli. Despite these under-predictions and failures, the ODOG model was quite successful overall and accounted for approximately 80% of the total variance in the brightness matches and in the lightness matches made in the absence of a shadow or transparent overlay. It remains an important and open question whether the observed under-predictions and failures are due to known limitations of the ODOG model or require other (possibly higher-level) explanations. We plan to address this question with a modified and more physiologically based model that uses Gabor filters as opposed to the current ODOG filters, and local contrast normalization as opposed to the current global normalization.

Research Highlights

Brightness and lightness matching were studied in seven visual illusions.

Lightness and brightness differed only for test patches in shadow or beneath a transparency.

Lightness matches differing from brightness matches were inferential (not sensory) judgments.

Spatial filtering accounts for most brightness percepts.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work was supported by grants R01 EY014015 (BB) and NIH P20 RR020151/P20 GM103505 (MEM). The National Center for Research Resources (NCRR), the National Institute of General Medical Sciences (NIGMS) and the National Eye Institute (NEI) are components of the National Institutes of Health (NIH).

The authors thank Huanzhong (Dan) Gu for programming assistance.

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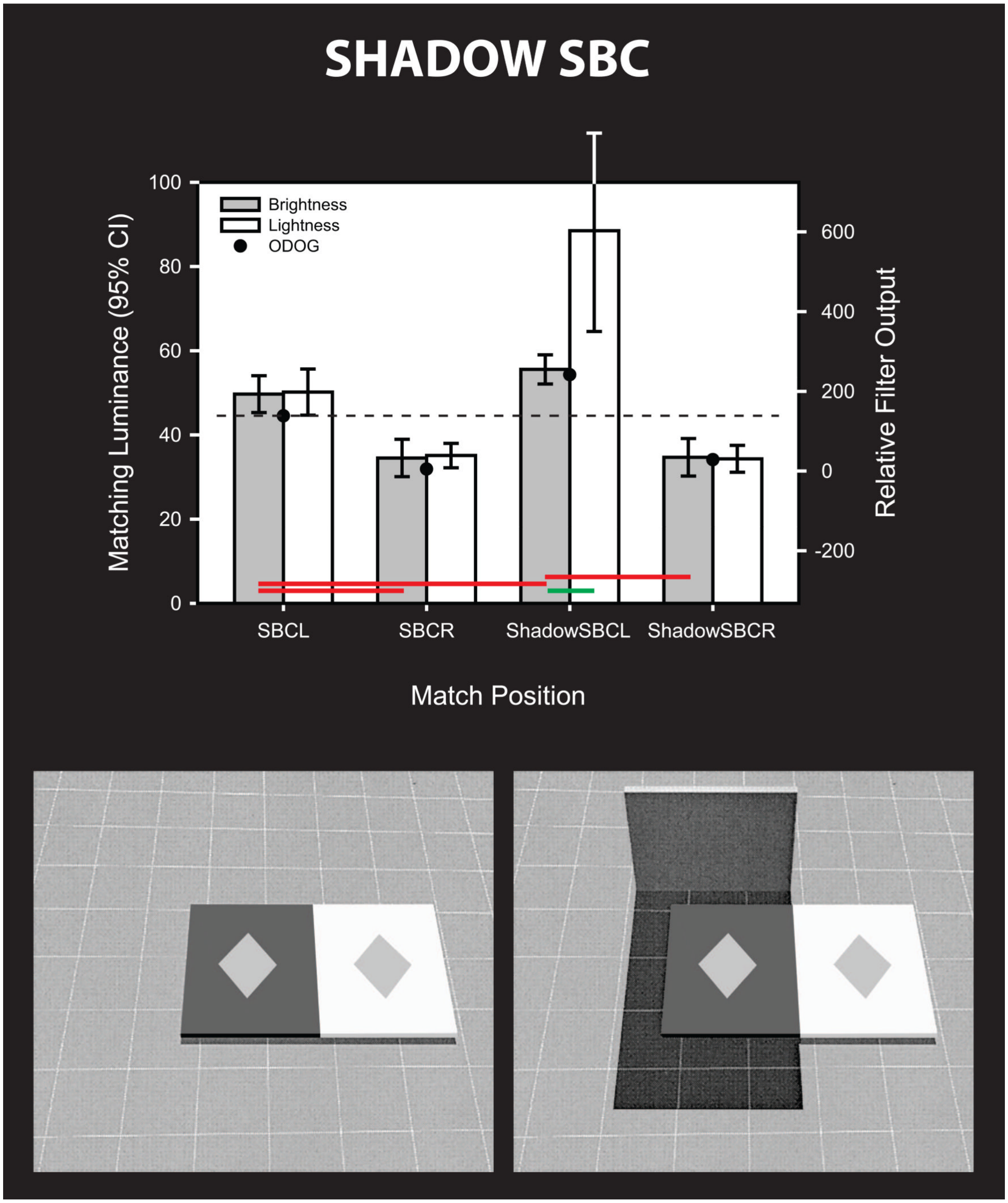

Fig. 1. Shadow Simultaneous Brightness/Lightness Contrast Illusion
Images illustrating the homogeneously illuminated Control (left) and shadowed Experimental (right) versions of the simultaneous brightness/lightness contrast illusion (SBC) of Williams et. al. (1998). The Control condition demonstrates the classic simultaneous brightness/lightness contrast effect in which a gray test patch on a low luminance background appears brighter/lighter than an identical test patch on a high luminance background. In the Experimental stimulus the test patches and near backgrounds are identical to those in the Control stimulus; however, a dark far surround has been added that causes the left half of the stimulus to appear to be in shadow. The bar graph plots the mean of the four observers mean brightness (gray bars) and lightness (white bars) matches

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for each test patch within the stimulus displays. The test patches are labeled left to right in the order that they appear in the stimuli: Control SBC Left (SBCL); Control SBC Right (SBCR); Experimental SBC Left (ShadowSBCL); Experimental SBC Right (ShadowSBCR). The error bars depict 95% confidence intervals. Test Patch luminance is indicated by the dashed line. Lightness matches only differed significantly from Brightness matches (green bar) in the Experimental stimulus where one of the test patches was seen beneath a shadow. Under these conditions subjects are able to make inferential or projective judgments of lightness (i.e., to discount the shadow or transparency to estimate the reflectance of the underlying surface). Significant Holm-Bonferroni-corrected pair-wise comparisons for Brightness matches are indicated by the red bars. The filled symbols represent the predictions of the ODOG model (Blakeslee & McCourt, 1999).

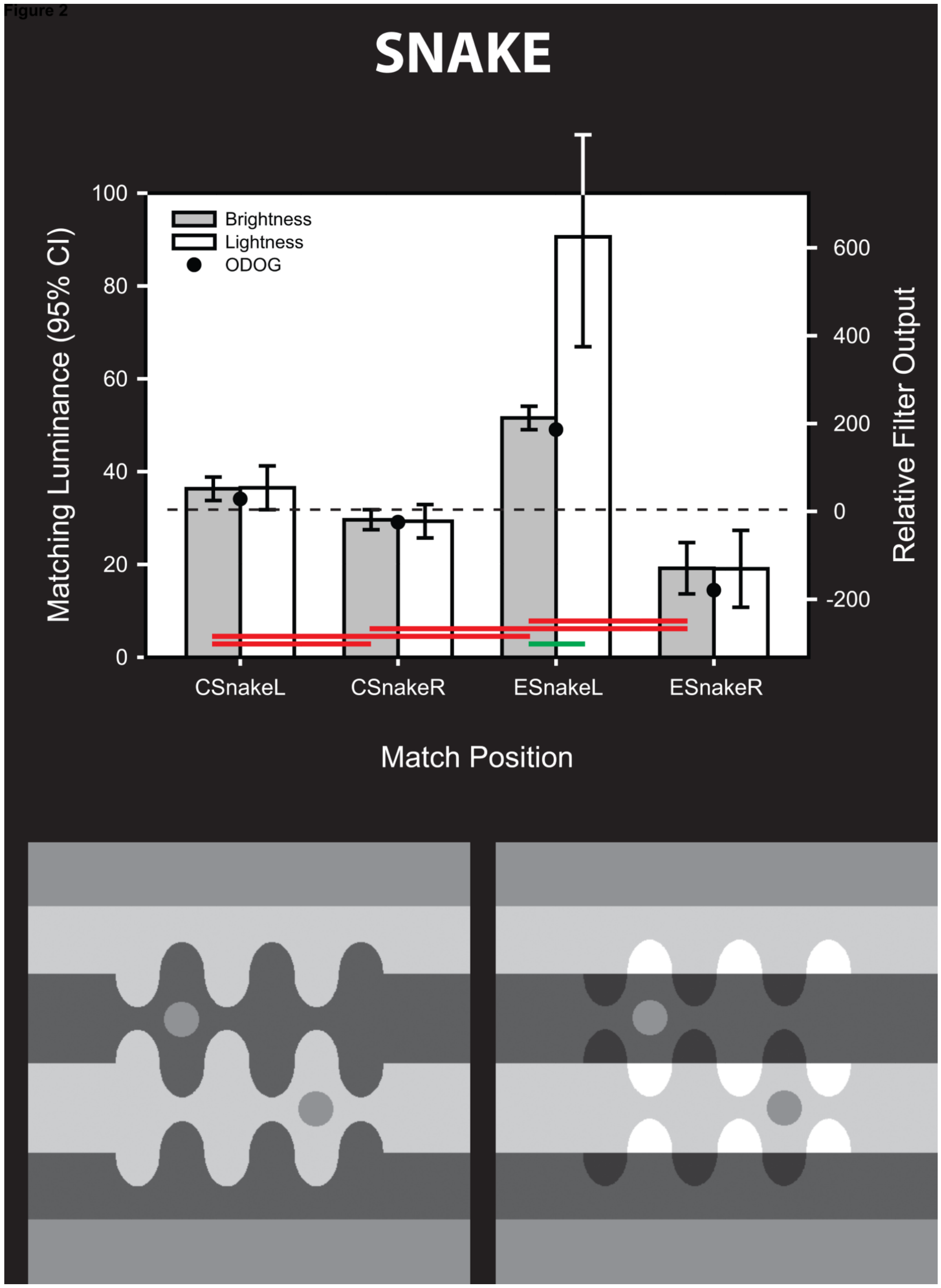

Fig. 2. The Snake illusion

The test patches in the Control (left) and Experimental (right) Snake stimulus images (Adelson, 2000) share the same luminance. In addition, the upper test patches in both stimuli have the same lower background luminance and the lower test patches share the same higher background luminance. The Experimental stimulus differs from the Control, however, in the luminances of more distant regions (the Snake undulations) that cause the upper test patch to appear to lie beneath a transparent overlay. The bar graph plots the mean of the four observers mean brightness (gray bars) and lightness (white bars) matches for each test patch within the stimulus displays. The test patches are labeled left to right in the order that they appear in the stimuli: Control Snake Left (CSnakeL); Control Snake Right (CSnakeR);

Experimental Snake Left (ESnakeL); and Experimental Snake Right (ESnakeR). All other details and results are the same as in Fig. 1.

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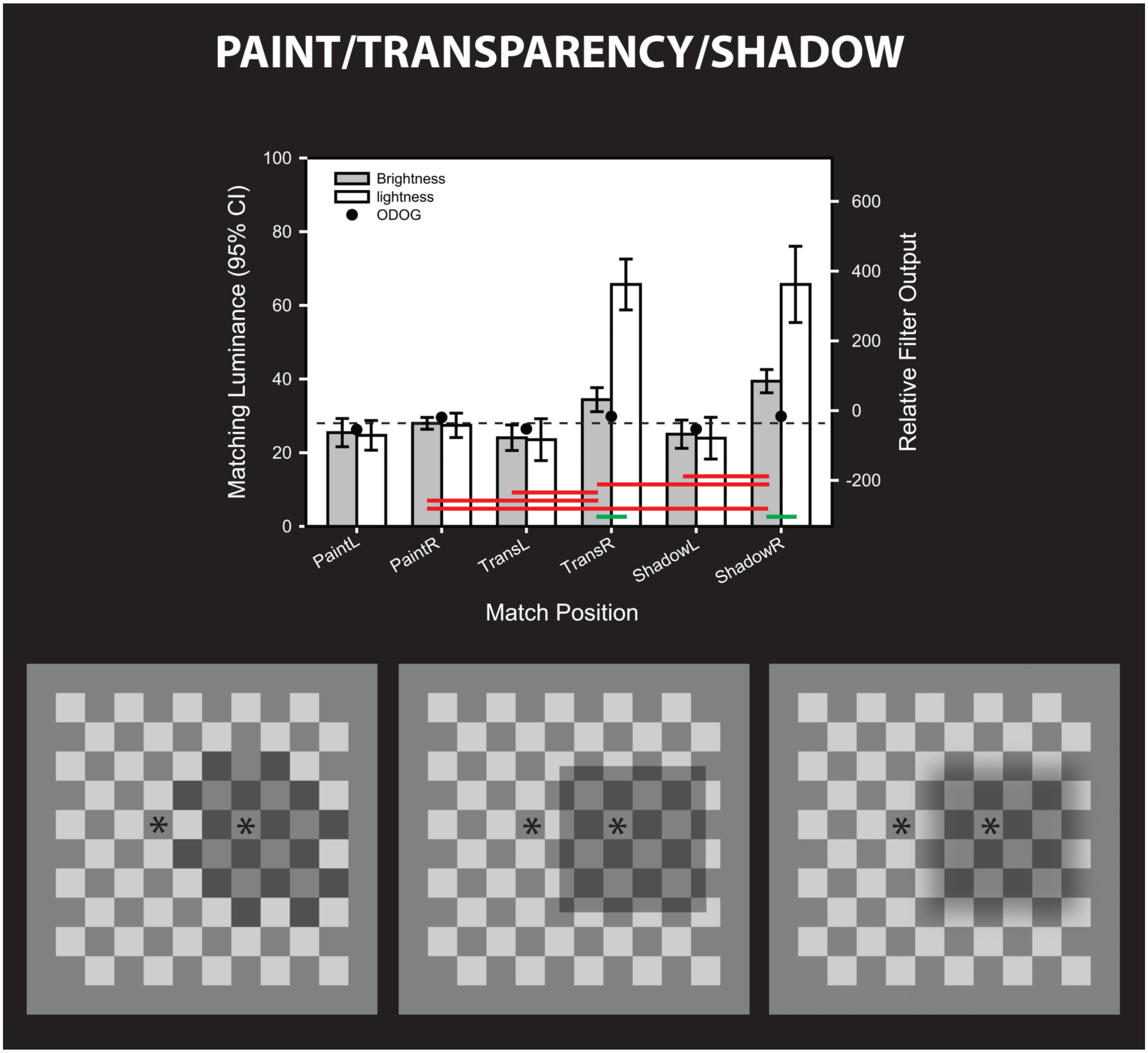

Fig. 3. The Paint/Transparency/Shadow illusion

Images depicting three versions of a checkerboard stimulus. The Shadow (Experimental) condition (right) is a nonhomogeneous illumination condition similar to the original Checkershadow illusion (Adelson, 1995). The sharp-edged version (middle) creates a second Experimental stimulus in which the impression of illumination nonhomogeneity is of a dark transparent overlay (Transparency condition). Illumination appears homogeneous in the Paint (Control) condition (left). The checks that serve as test patches (marked by asterisks) are identical in luminance and are each immediately surrounded by checks of the same luminances. The distribution of luminances defining the edges of in the region containing the darker checks, however, differs. The bar graph plots the mean of the four observers mean brightness (gray bars) and lightness (white bars) matches for each test patch. The test patches are labeled left to right in the same order that they appear in the stimuli below: Paint Left (PaintL); Paint Right (PaintR); Transparency Left (TransL); Transparency

Right (TransR); Shadow Left (ShadowL); Shadow Right (ShadowR). All other details and results are the same as in Fig. 1.

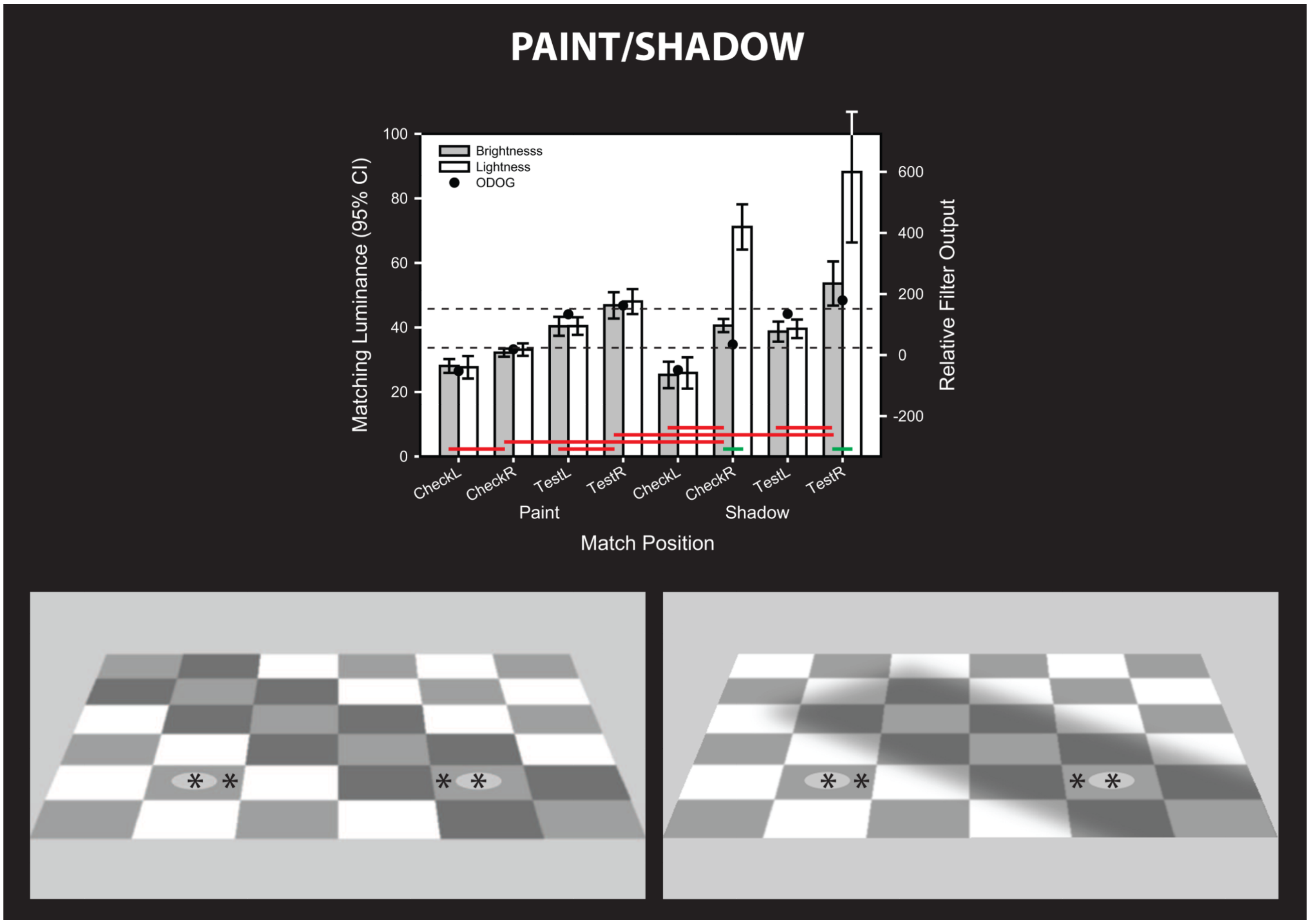

Fig. 4. The Paint/Shadow Illusion

The left image illustrates the homogeneously illuminated Paint (Control) and the right image the Shadow (Experimental) condition of the Paint/Shadow illusion (Hillis & Brainard, 2007). The matching locations (marked by asterisks) include both the test patches and their immediate background checks. Test patch luminance and background check luminance are identical both within and between Experimental and Control stimuli. The stimuli differ, however, in the pattern of luminance defining the edges of the region containing the darker checks. The bar graph plots the mean of the four observers mean brightness (gray bars) and lightness (white bars) matches for each test region within the stimulus displays. The test regions are labeled left to right in the order that they appear in the stimuli: Paint Check Left (CheckL); Paint Check Right (CheckR); Paint Test Left (TestL); Paint Test Right (TestR); Shadow Check Left (CheckL); Shadow Check Right (CheckR); Shadow Test Left (TestL); Shadow Test Right (TestR). All other details and results are the same as in Fig. 1.

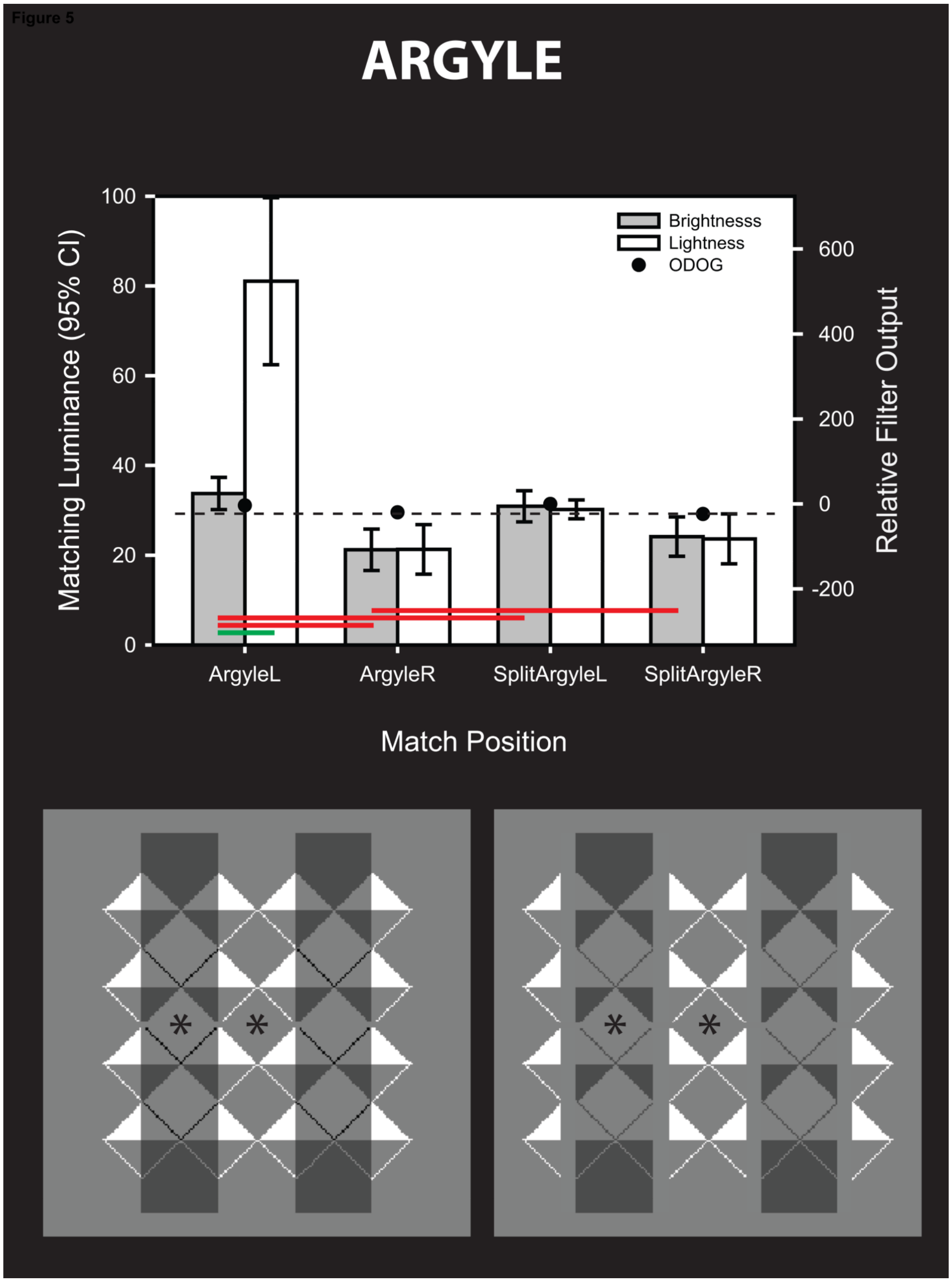

Fig. 5. The Argyle illusion

Images depicting the Experimental (left) and standard Control (right) versions of the Argyle illusion (Adelson, 1993). The test patches of interest are indicated by asterisks. The left test patch in the Experimental argyle stimulus (but not the central test patch) appears to be under a dark transparent strip. In the Control stimulus illumination appears homogeneous. Although test patch luminance and local (border) luminance contrast are identical in these two stimuli, the luminances of more distal regions differ. The bar graph plots the mean of the four observers mean brightness (gray bars) and lightness (white bars) matches for each test patch. The test patches are labeled left to right in the order that they appear in the stimuli below: Experimental Argyle Left (ArgyleL); Experimental Argyle Right (ArgyleR); Control

Argyle Left (CArgyleL); Control Argyle Right (CArgyleR). Other details and results are the same as in Fig. 1.

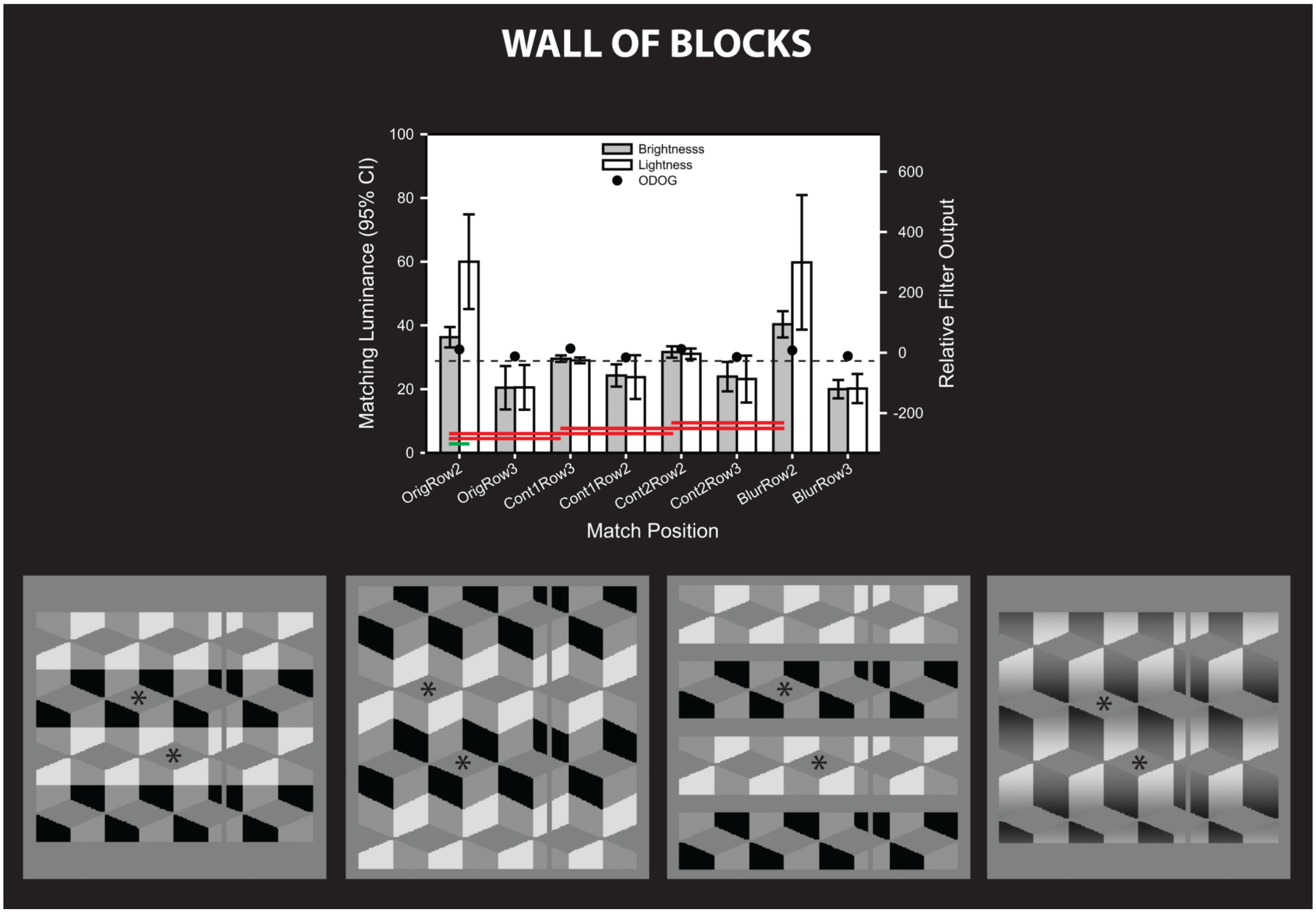

Fig. 6. Wall of Blocks

Images illustrating four versions of the Wall of Blocks stimulus (Adelson, 1993; Logvinenko, 1999; Logvinenko & Ross, 2005). In the original Wall of Blocks stimulus (left) illumination of the test patches (marked by asterisks) appears to vary because the upper test patch seems to be covered by a dark transparent strip. The two central images are control conditions for the original stimulus in which illumination of the test patches appears homogeneous. In the rightmost stimulus the illumination edges are blurred across the stimulus such that, as in the original stimulus, the upper test patch appears more dimly illuminated than the lower test patch. Although test patch luminance and local (border) luminance contrast are matched in the original stimulus and the two controls (although the position of the matching control patch is switched in Control 1), the luminances of more distal regions differ. The bar graph plots the mean of the four observers mean brightness (gray bars) and lightness (white bars) matches for each test patch within the stimulus displays. The test patches are labeled left to right in the order that they appear in the stimuli below: Experimental Wall of Blocks Row 2 (OrigRow2); Experimental Wall of Blocks Row 3(OrigRow3); Control 1 Row 3 (Cont1Row3); Control 1 Row 2 (Cont1Row2); Control 2 Row 2 (Cont2Row2); Control 2 Row 3 (Cont2Row3); Blur Row 2 (BlurRow2); and Blur Row 3 (BlurRow3). Other details and results are the same as in Fig. 1.

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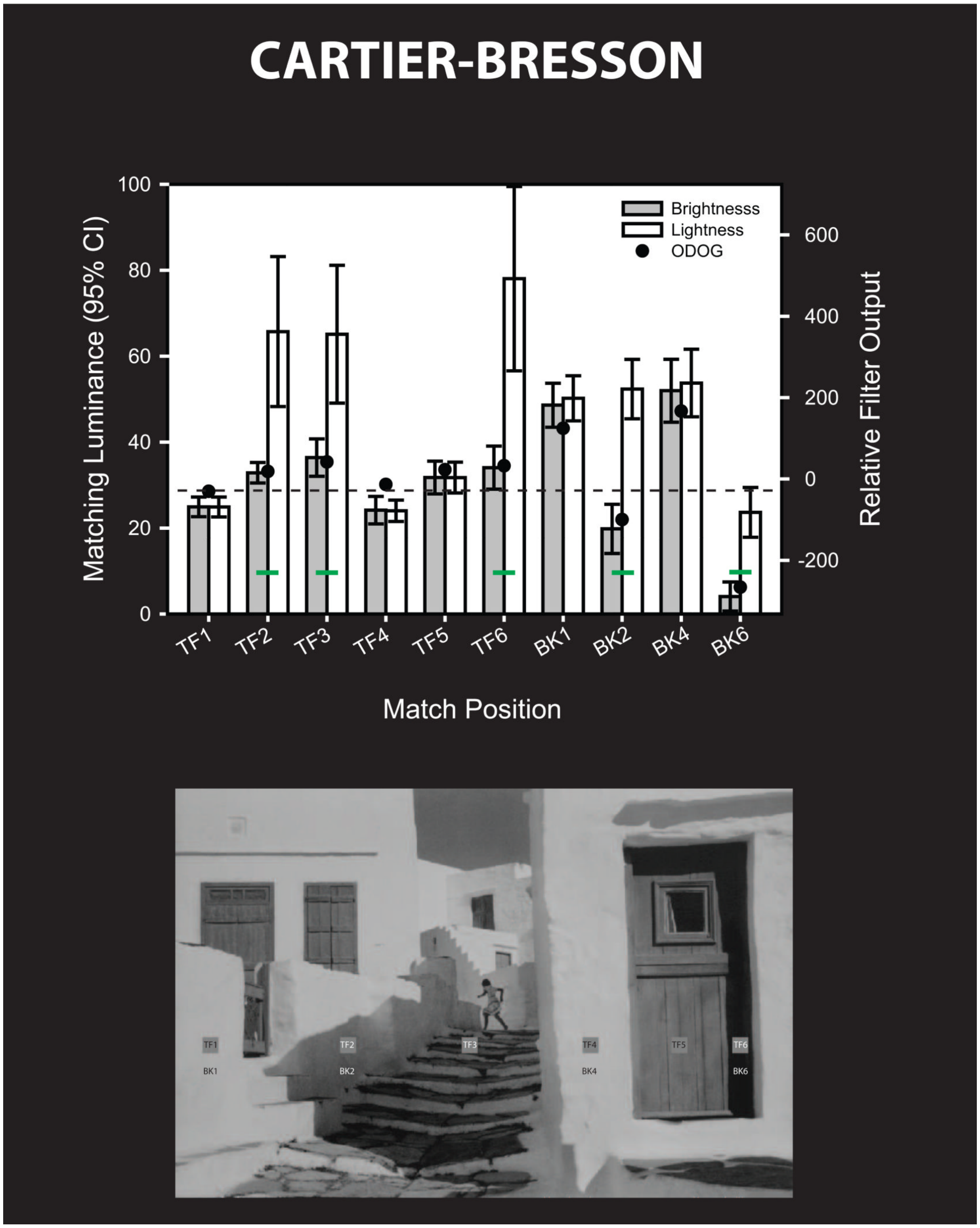

Fig. 7. Cartier-Bresson photograph

An image of the Cartier-Bresson photograph stimulus including the six test patches. The test patches are labeled from left to right (TF1–TF6). In addition, four background regions located below the test patches were selected for matching and are labeled: BK1, BK2, BK4, and BK6. The luminance of all of the test patches is identical, however, their backgrounds differ as in the classic simultaneous brightness/lightness contrast stimulus. The bar graph plots the mean of the four observers mean brightness (gray bars) and lightness (white bars) matches for each test patch and background patch within the stimulus. The error bars depict 95% confidence intervals. As for all of the Experimental stimuli, Lightness matches differed significantly from Brightness matches (green bars) at locations where the test patch was seen beneath a shadow. The filled symbols represent the predictions of the ODOG model (Blakeslee & McCourt, 1999).

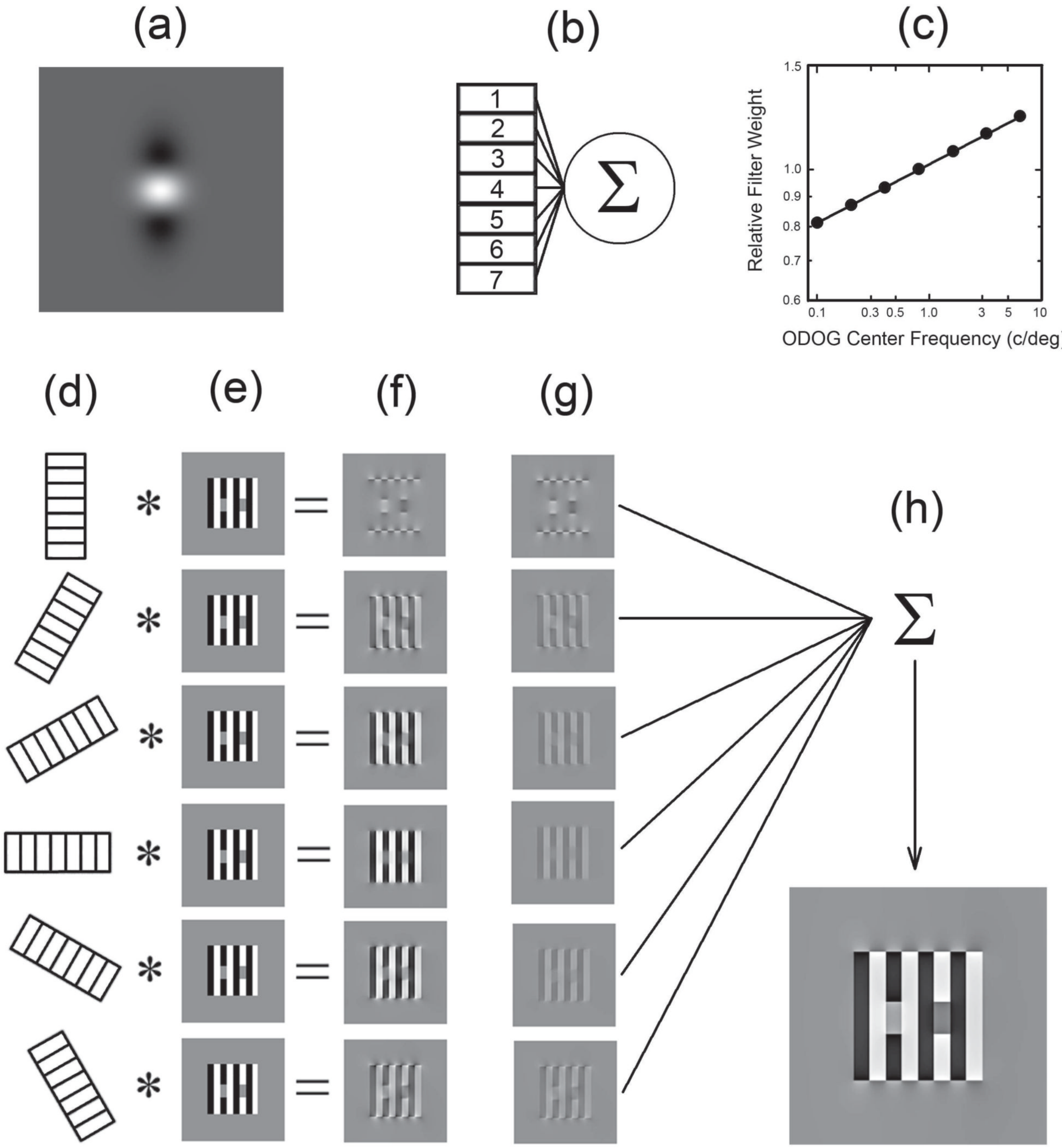

Fig. 8.
A diagrammatic representation of the oriented difference-of-Gaussian (ODOG) model. (a) A gray level representation of an ODOG filter. The oriented filters of the ODOG model are produced by setting the ratio of DOG center/surround space constants to 1:2 in one orientation and to 1:1 in the orthogonal orientation. (b) The ODOG model is implemented in 6 orientations (0, 30, 60, 90 −30 and −60 degrees relative to vertical). Each orientation is represented by seven volume-balanced (i.e., integrate to 0) filters that possess center frequencies arranged at octave intervals (from 0.1–6.5 c/d). The seven filters (b) within each orientation are summed after weighting across frequency using a power function with a slope of 0.1 (c). This slope is consistent with the shallow low-frequency fall-off of the

suprathreshold contrast sensitivity function (Georgeson & Sullivan, 1975). The resulting six multiscale spatial filters, one per orientation, are convolved with the stimulus of interest (d–e). The filter outputs (f) are normalized across orientation by dividing each by its space-averaged root-mean-square contrast, as computed across the entire convolution output (g). The six normalized outputs are summed to produce the final ODOG model output (h).

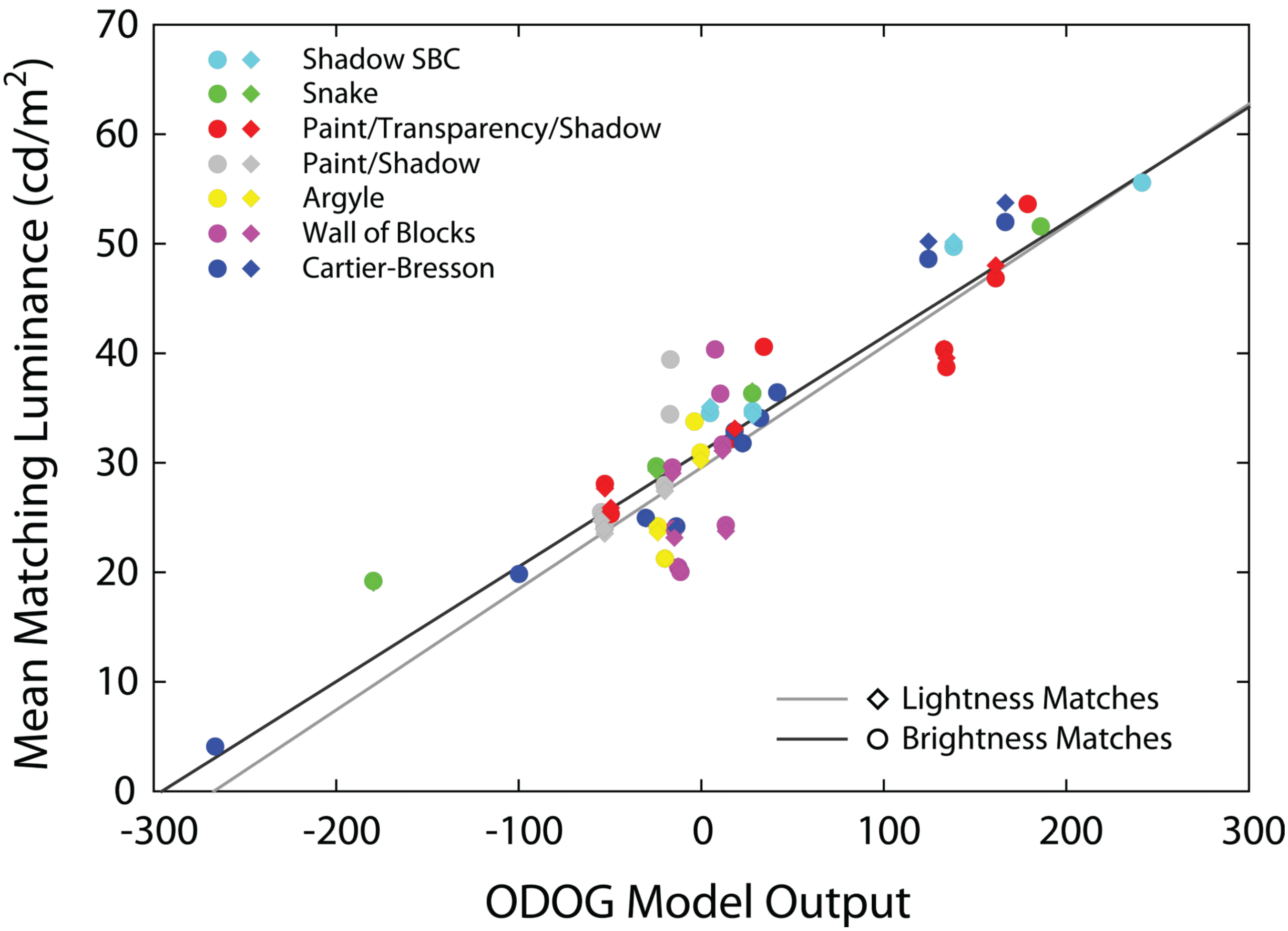

Fig. 9.

A graph of the brightness matches (circles), as well as the lightness matches from the conditions that did not contain a shadow or transparent overlay (diamonds) plotted against the ODOG model predictions for these same matches. The different colors indicate matches for the various stimuli. The ODOG model as currently implemented accounts for a significant proportion ($R^2 = 0.826$; black line) of the total variance in the brightness matches ($p < 0.001$) and in the lightness matches ($R^2 = 0.787$; gray line) made in the absence of a visible illumination component ($p < 0.001$).