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The perceptual contrast of impossible shadow edges

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Abstract

Luminance ratios along shadow edges remain the same even when they cross reflectance borders. According to Gilchrist (1988, P&P 43(5) 415-424) this so-called ratio invariance property is a crucial factor to shadows perception. However, Soranzo and Agostini (2004, Perception 33 (11) 1359-1368) suggested that in some conditions (named Impossible Shadows) a luminance pattern might still be perceived as a shadow even if the ratio invariance property along its edge is violated. This can occur when an edge is collinear with another edge (Contextual edge) which incorporates it, shares the same polarity, and generates a larger ratio. In the present study, the hypothesis that Impossible Shadows are actually perceived as shadows is tested by comparing the perceptual contrast of a luminance edge in absence of a Contextual edge (Control condition), to that of both Possible Shadow edges (where the Contextual and Mediating edge share the same ratio) and Impossible Shadow edges (where the ratio at the Contextual edge was larger rather then that at the Mediating edge). We found that the perceived contrast of luminance edges shrinks in both Possible and Impossible Shadow conditions rather then in the Control condition. This evidence supports the hypothesis that a luminance pattern might be perceived as a shadow even if the ratio invariance property is violated.

1. Introduction

How can the visual system recognize the difference between an illumination edge (i.e. a change in the intensity of the light on a surface) and a reflectance edge (i.e. a change in the molecular structure on a surface), in spite of the fact that, at the retinal level, there are just indistinguishable luminance discontinuities?

Many attempts to address this problem have been made by vision scientists. It has been suggested, for example, that the sharpness/graduality of the edge luminance profile might be an important cue for distinguishing a reflectance edge from an illumination edge, respectively (Hering, 1878/1964; Kardos, 1934; MacLeod, 1947; Kanizsa, 1954; McCourt, 1982; Moulden and Kingdom, 1991; Schirillo and Shevell, 1997; Agostini and Galmonte, 1997a, 1997b, 2002, Soranzo et al, submitted). The surface object three-dimensional orientation in relation to the light source can also be considered a cue informing the visual system of the edge type (Gilchrist, 1979; Pessoa, Mingolla and Arend, 1996; Ripamonti et al. 2004). However, the problem persists when considering sharp edges on flat surfaces. For these cases, Gilchrist (1988) suggests that the critical factor for edge recognition is the nature of the intersection where an illumination edge crosses a reflectance one. This intersection possesses the so-called ratio invariance property that is the luminance ratio between regions crossed by an illumination edge remains the same. According to this property, in order for a *physical* illumination edge to be actually *perceived* as an illumination edge, it has to cross at least one reflectance border, so that there are two regions sharing the same ratio; or, better, the illumination edge produces two collinear luminance edges giving rise to the ratio invariance property. If, on the other hand, the illumination edge does not cross any reflectance border, it should be perceived as a reflectance edge. Specifically, Gilchrist (1988) has shown that when the intersection between an illumination and a reflectance edge is hidden from view, the illumination edge is perceived as a reflectance edge. This is exemplified in figure 1.

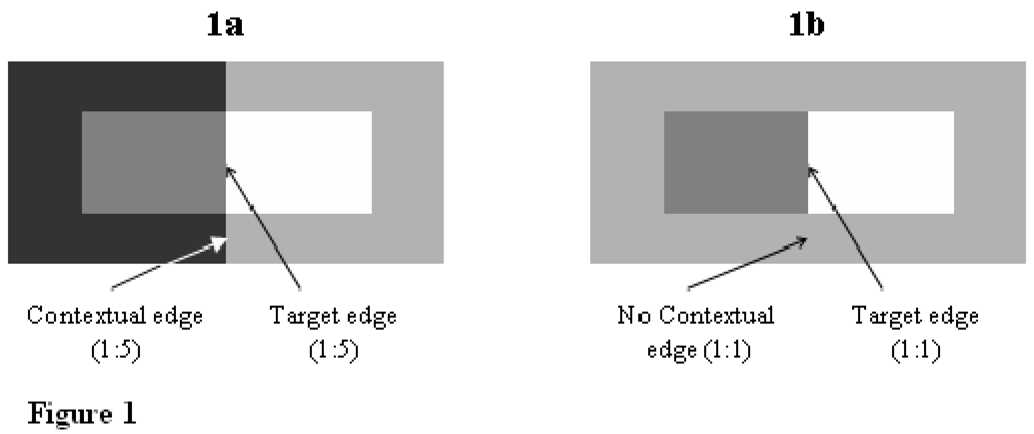

Figure 1. The same 1:5 luminance ratio at an edge (Target edge), will be perceived either as an illumination edge when it is incorporated within a collinear Contextual edge sharing the same polarity and the same ratio (a) or a reflectance edge if there is no Contextual edge (b).

This explanation implies that a sharp luminance edge on a flat surface will be perceived as an illumination edge only if it is collinear with at least another edge maintaining the ratio invariance property. However, Soranzo and Agostini (2004) proposed that in some conditions a luminance edge might still appear as an illumination edge even if the ratio invariance property is violated. This occurs when the edge is collinear with another edge (Contextual edge) which incorporates it and generates a larger ratio. So, for example, if the luminance ratio at an edge (Target edge) is 1:5 whilst the luminance ratio at a Contextual edge is 1:10, the ratio invariance property is violated, but the Target edge might still appear as an illumination edge (see figure 2).

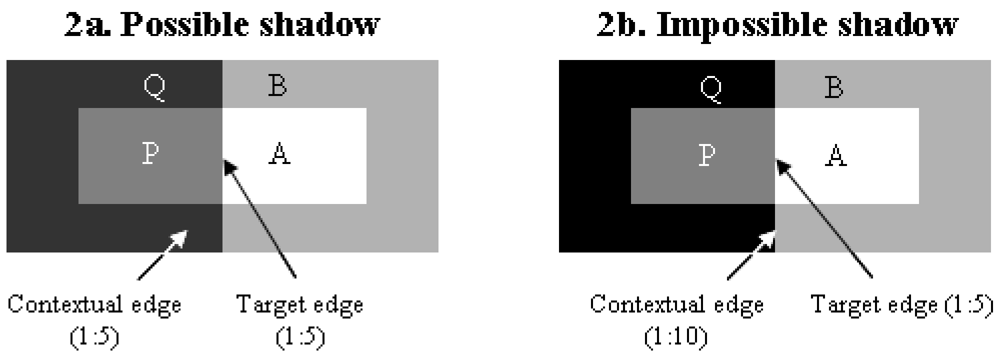

Figure 2

Figure 2. (a) Possible shadow: Target and Contextual edge share the same polarity and ratio. (b) Impossible shadow display: the ratios at the Target and the Contextual edge are different but the Target edge is still perceived as an illumination edge.

Soranzo and Agostini (2004) named these conditions “impossible shadows” because they fallaciously give rise to the appearance of being shadows[1], even if their edges violate the physical property of ratio invariance.

This can be better illustrated by applying the luminance-based Metelli’s (1975) episcotister model. In both displays of figure 2, A and B are the higher and the lower luminance, respectively, corresponding to the lighter and darker surface; P and Q are the luminance of the same surfaces, respectively, that are covered by the semi-transparent medium.

According to Metelli’s (1975) model, the luminance of the reflective component of a semi-transparent medium can be calculated as follow:

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[1] It has to be noticed that the sharpness of the Mediating and Contextual edge might favour the impression of a filter rather than a shadow. However, according to Metelli (1975) shadows are indistinguishable from filters of virtually no reflectance (i.e. 0% reflectance). Being that only virtual, rather than real, filters possess the ratio invariant property we may consider virtual filters at the same way as shadows.

$$L = AQ - BP / (A+Q) - (B+P). \quad (1)$$

Shadows, of course, do not have a reflective component. Indeed, when applying this formula to shadows, *L* results to be zero because *AQ* equals *BP*.

Impossible shadows are those luminance patterns that are perceived as being shadows (or semi-transparent layers) but that cannot physically be shadows because the luminance of their reflective component (*L)* should be lower than zero. It occurs when *AQ* is lower than *BP*.

The present research investigates the Impossible Shadow phenomenon further using another visual phenomenon, which is the reduction of the perceptual contrast of shadows edges. Kardos (1934, p. 6) pointed out that "perception in the natural, naive, object-oriented mode does not involve the organization of the visual field into shadows and non-shaded regions, comparable, for example, with the organization into figure and ground. The shadow is normally not salient as a visual gestalt". A prediction arising from Kardos' saliency idea is that the perceptual contrast of a luminance edge shrinks when the edge appears as an illumination rather than a reflectance edge. Indeed, when a shadow is made to appear as a stain by hiding the collinear edges giving rise to the ratio invariance property, the same area of the visual image should be more salient in this new condition. Consequently, its edge will also be perceived as more salient and more contrasted. An experimental study conducted by Soranzo and Logvinenko (2005) showed that this is actually the case: the *perceived* contrast of a physical illumination edge increased when it was made to appear as a reflectance edge by hiding the collinear edges giving raise to the ratio invariance property.

In order to test the hypothesis that Impossible Shadows have the appearance of shadows, the present study measures the perceived contrast of their edges. The key distinction, underlying this project is that if Impossible Shadows do appear as shadows, then their edges must be perceived as illumination edges and therefore the perceptual contrast of their edges must shrink when compared to equal edges appearing as reflectance edges.

2 Experiment

2.1. Method

2.1.1 Observers

13 volunteer observers participated in this experiment. All had normal or corrected-to-normal vision and were naïve as regards the experimental design.

2.1.2 Apparatus and stimuli

The stimuli were all generated by a Pentium computer and were presented on a carefully calibrated 18-inch 523X Daewoo monitor (944 x 648 pixels). Figure 3 represents the experimental and control displays.

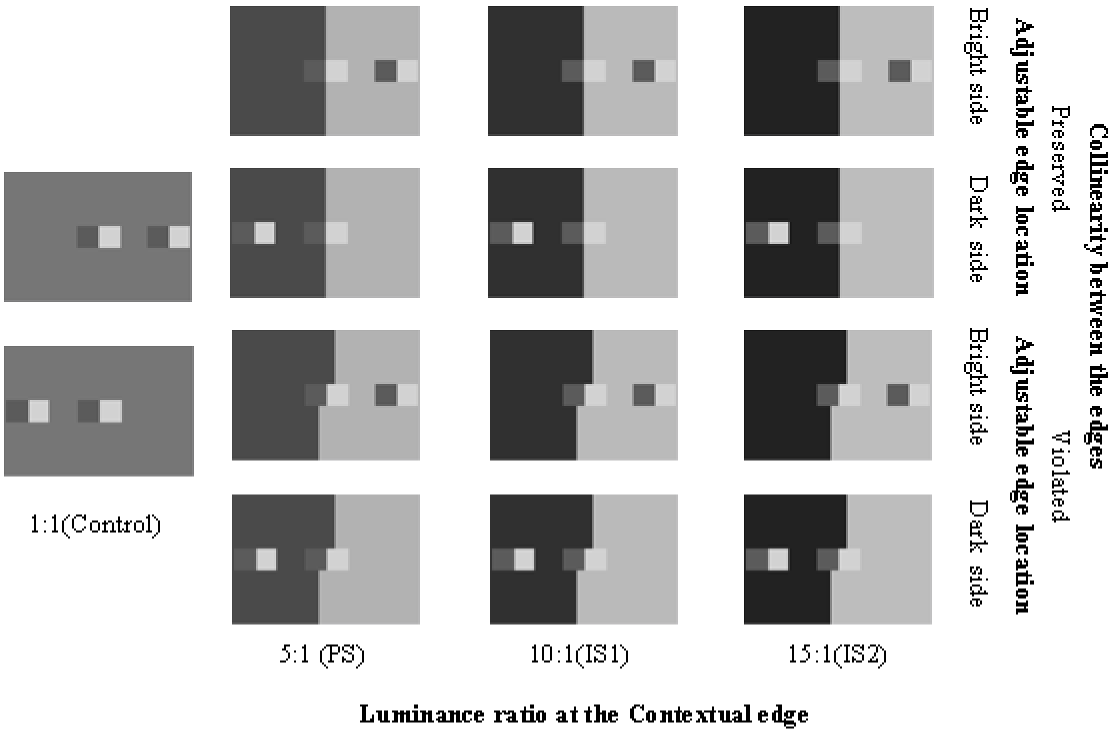

Figure 3

Figure 3 shows the displays used in the experiment. They are grouped in columns, according to the level of the luminance ratio at the Contextual edge variable; and rows, and according to both the level of the Collinearity between the edges and the level of the Adjustable edge location variables.

The Contextual edge was the edge between the two sides of the screen, subtending 10 x 14 deg of visual angle each. The luminance of the two sides of the screen varied according to the Luminance ratio at the Contextual edge variable. The geometric mean between the two sides of the screen (referred as the “dark” and “bright” side, respectively) was kept constant (16.8 cd/m^2).

The Luminance ratio at the Contextual edge variable had three levels: 1:5 (possible shadow), 1:10 (Impossible shadow 1), and 1:15 (Impossible shadow 2). In addition, there was a Control condition where the luminance ratio at the Contextual edge was 1:1. The following table lists the luminance of the two sides of the screen:

Luminance ratio at the Contextual edge	**Dark Side**	**Bright Side**
1.1 (Control)	16.8	16.8
1:5 (Possible Shadow)	7.5	37.8
1:10 (Impossible Shadow 1)	5.3	53.5
1:15 (Impossible Shadow 2)	4.4	65.1

Table 1. Luminance in cd/m^2 of the Dark and Bright side of the screen as a function of the Luminance ratio at the Contextual edge variable.

A Target edge was created by two squares subtending 3x3 deg of visual angle each, the luminance was 18 and 89.8 cd/m^2, respectively, giving rise to a 1:5 luminance ratio. The Target edge coincides with the middle of the screen.

By applying equation (1) to these conditions, L equals 0 cd/m^2 in the Possible Shadow condition; -20.64 cd/m^2 in the Impossible Shadow 1 condition; -71.42 cd/m^2 in the Impossible Shadow 2 condition.

The Adjustable edge was formed by two additional squares having the same size as the two squares shaping the Target edge (3x3 deg of visual angle). These additional squares could be located either on the dark or on the bright side of the screen, according to the Adjustable edge location variable. In this way, the Adjustable edge was made to appear as a reflectance edge because it did not have any Contextual edges. When this couple of squares was presented on the dark side, the luminance of the right hand square was fixed (89.8 cd/m^2; i.e. the same luminance of the right hand square shaping the Target edge), while the luminance of the other square was adjustable from the computer console. Symmetrically, when the couple of squares was presented on the bright side, the luminance of the left hand square was fixed (18 cd/m^2, i.e. the same luminance of the left hand square shaping the Target edge) while the luminance of the other square was adjustable from the computer console. The luminance of the adjustable squares was randomly assigned by the software at the beginning of each trial.

The third independent variable was the Collinearity between the edges: The Contextual edge could be either collinear with the Target edge or misaligned. When it was collinear, both the Target and Contextual edges were placed in the middle of the screen. In the misaligned condition, the upper portion of the Contextual edge was shifted 1 deg. of visual angle toward the bright side of the screen, whilst its bottom portion was shifted toward the dark side by the same degree. This variable intended to control for the lightness induction amongst the area.

To sum up, there were 14 displays organized in three independent variables:

1) Luminance ratio at the Contextual edge (1:5,1:10,1:15 plus a Control 1:1);
2) Adjustable edge location (Dark side, Bright side);
3) Collinearity between the edges (Preserved, Violated).

2.1.3 Procedure

Observers viewed the stimuli, presented in random order, in a darkened room from a distance of 67 cm from the monitor. They were instructed to match the perceived contrast of the Target edge by adjusting the luminance of one of the two squares shaping the Adjustable edge depending on the Adjustable edge location variable (see previous section). Observers performed this task by using the plus and minus keys of the keyboard. Pressing another key signalled that a satisfactory match was achieved; at that point, the ratio assigned by the observers to the Adjustable edge was recorded and the next trial began. The observers performed four matches for each of the 14 stimuli, so they provided fifty-six adjustments. Each display was left on the screen as long as needed to produce the match. The whole session lasted about thirty-five minutes.

2.2 Results and discussion

Mean ratings are obtained by dividing the *physical contrast* at the Target edge with the ratio assigned by the observers to the Adjustable edge (*perceived contrast*). In this way, 1 indicates an exact match, whilst values above 1 indicate a reduction of the perceived contrast of the Target edge. The transformed observers' mean ratings, together with the standard errors, are shown in figure 4.

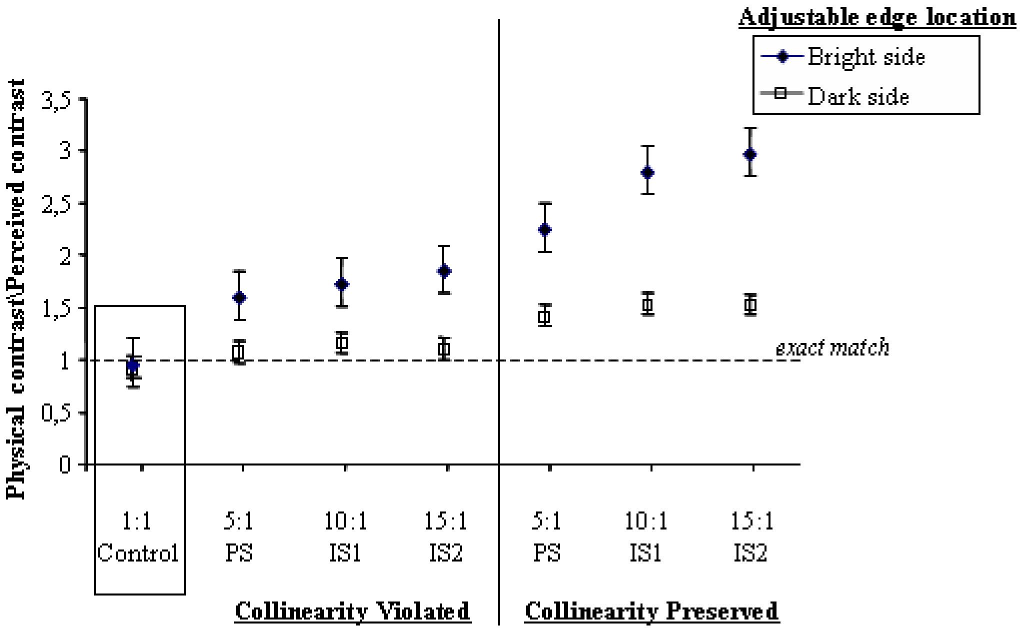

Figure 4

Figure 4 shows the results of the experiment. Mean ratings are obtained by dividing the physical ratio (5) with the contrast assigned by the observers to the Adjustable edge. Bars indicate standard errors.

A Kolmogorov-Smirnov test performed upon the row data was non-significant, so that the normality of the data distribution was assumed. A three-way repeated measure ANOVA, conducted on the transformed data, revealed a significant effect of the three independent variables: Luminance ratio at the Contextual Edge [$F_{(2,24)} = 6.63$; $p. < 0.01$]; Adjustable edge location [$F_{(1,12)} = 135.93$; $p. < 0.01$]; and Collinearity between the edges [$F_{(1,12)} = 47.27$; $p. < 0.01$]. The interaction between the Adjustable edge location and the Collinearity between the edges was also significant [$F_{(1,12)} = 16.07$; $p. < 0.01$], whilst the other interactions were not. For the Control conditions, two paired t tests revealed that they did not differ significantly from 1, indicating that the observers were able to perform the task.

As can be seen from the graph, the Target edge perceived contrast shrinks when the luminance ratio at the Contextual edge increases, independently from the violation of the ratio invariance property. This effect is stronger for the Bright side condition of the Adjustable edge location variable. In addition, when the collinearity between the Contextual and the Target edge is maintained, the perceived contrast of the Target edge shrinks compared to the correspondent conditions where it is violated. Finally, the significant effect of the interaction between the Adjustable edge location and the Collinearity between the edges variables seems to indicate that the location of the Adjustable edge affects the perceived contrast of the Target edge mainly when the collinearity between the Target and Contextual edge is preserved.

3. Discussion

In the present study, the hypothesis that Impossible Shadows are perceived as shadow is tested by measuring the perceptual contrast of their edges. It is known that the perceptual contrast of a luminance edge shrinks when it appears as an illumination rather then a reflectance edge (Soranzo and Logvinenko, 2005). The key distinction, underlying this study, is the following: If Impossible Shadows do appear as shadows, then their edges should be perceived as illumination edges; and, consequently, the perceptual contrast of their edges should shrink when compared to equal edges appearing as reflectance edges.

To test this assumption, in a CRT experiment, the perceived contrast of a 1:5 luminance ratio Target edge was measured in conditions where it was incorporated within a Contextual edge having i) the same ratio (possible shadow display), ii) a larger ratio (impossible shadow display), and iii) a 1:1 ratio (reflectance edge display). To control for the lightness induction amongst the areas on the screen, the collinearity between the Target and Contextual edge was also manipulated; the two edges could be either collinear or misaligned. Results showed that the perceived contrast of the Target edge shrank in both possible and impossible shadow displays rather than in the control displays. This effect was stronger when the Adjustable edge was presented on the bright side of the display, and when the collinearity between Target and Contextual edges was maintained rather than violated. Outcomes support the hypothesis that impossible shadow edges are perceived as illumination edges in spite of the fact that the ratio invariance property is violated. Hence, it can be concluded that impossible shadows do appear as if they were shadows. It seems that, in order for distinguishing between an illumination and a reflectance edge, the visual system applies a simple heuristic:

When two collinear luminance edges - one including the other - share the same polarity, increasing the ratio at the including edge enhances the perception that these edges are portions of the same illumination edge.

Physiology of Impossible Shadows

This heuristic might descend from the neural organization of the visual cortex. Campbell and Robson (1968) proposed that the visual system filters the image into a number of relatively narrow spatial frequency bands, which were termed “channels”. Each of these channels can be understood as an array of linear filters with all filters in the array sharing the same receptive field profile, but centred at different retinal locations to cover the visual field. Each of these filters produces a positive or negative output in response to any given stimulus. Perceived contrast is proportional to the absolute value of filter output. According to Solomon, Sperling and Chubb (1993) the output values produced by these filters are subject to lateral inhibition from other filters in the same array. In particular, the higher the absolute value of the output of a filter in such an array, the greater its inhibitory effect on the other filters in the array.

The reduction of the Target edge perceived contrast, registered in the impossible shadow displays, might depend on the amount of lateral inhibition delivered to neurons tuned to the Contextual edge. We propose that this inhibition, at its turn, is “interpreted” - at a higher level of the visual process - as a change in the illumination intensity. The stronger the inhibition, the stronger this interpretation will be. The impossible shadow phenomenon might derive from the fact that there are no neurons devoted to cease this inhibitory activity. When the ratio equality between the Target and the Contextual edge is overtaken (creating an impossible shadow condition) no neurons signal for the illumination-edge incompatibility and the perception of an illumination edge is not stopped.

Phenomenology of Impossible Shadows

The impossible shadow phenomenon can be observed by using papers and lights, too. Place a white paper in the middle of a larger bipartite paper, half middle-grey and half dark-grey. Cast a shadow matching exactly the darker side of the larger paper and covering half of the smaller white paper. When looking at the middle of this configuration through a reduction screen, in such a way that only the two papers under illuminations are visible, what it is perceived are two homogeneously painted papers under two illuminations (figure 5). The smaller paper appears white, while the larger one appears as a homogenous grey. In other words, under these conditions, part of the darkness of the darker side of the larger paper is misperceived as a shadow rather than as a dark grey.

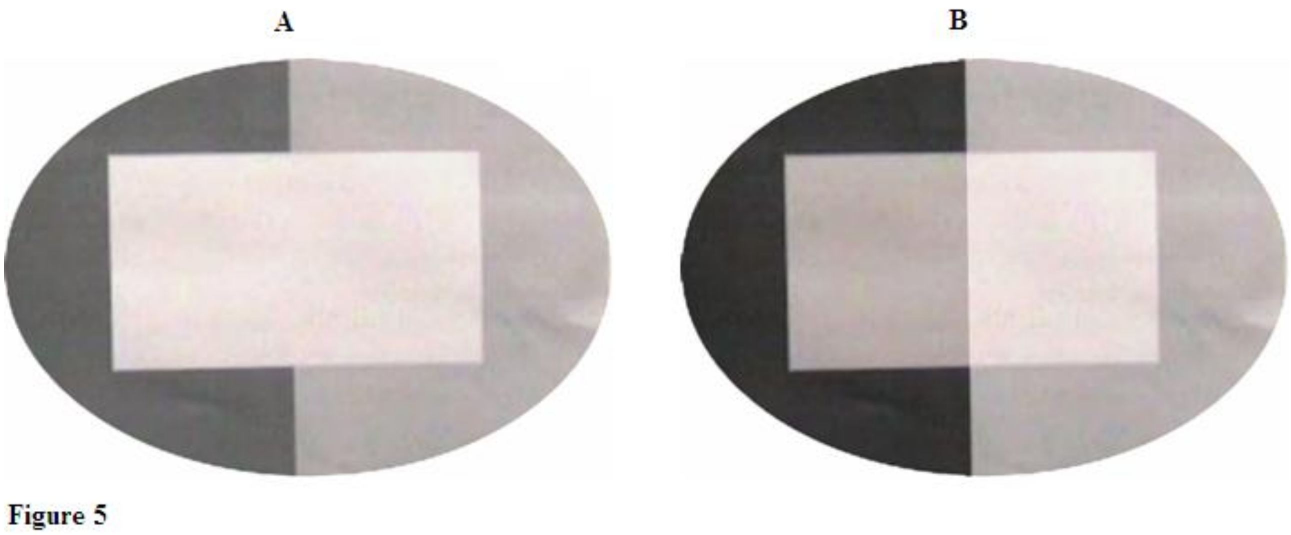

Figure 5. When, on a white paper on a bipartite background (a), a shadow is cast so to cover exactly the darker part of the background and half of the white paper, the background appears as a homogeneous grey partially shadowed (b).

Origins of the perceptual contrast shrinking

The effect of the Adjustable edge location variable might help understanding why the perceived contrast of a luminance edge shrinks when it appears as an illumination edge rather than a reflectance edge. This reduction could occur i) because the darker side of a (perceived) illumination edge appears lighter than the darker side of a (perceived) reflectance edge; ii) because the lighter side of a (perceived) illumination edge appears darker than the lighter side of a (perceived) reflectance edge; iii) because of both, the darker side appears lighter and the lighter appears darker. As the perceptual contrast of the Target edge was found to shrink largely when the Adjustable edge was located in the brighter side of the screen, it seems that the perceptual contrast shrink of the luminance edges being perceived as illumination edges occurs mainly because there is a lighting effect on the darker side. This is coherent with Zdravkovic, Economou and Gilchrist's findings (2006). Authors show that the perceived lightness of a homogeneous surface which is partially shadowed depends mainly from the luminance on its illuminated side rather than on its shadowed one. Hence, the perceptual contrast shrink of (perceived) illumination edges occurs because their darker side appears lighter than the darker side of a (perceived) reflectance edge

Evolutionary aspects of the Impossible shadows

What might be the evolutionary advantage of a system that perceives as shadows some luminance patterns that cannot be (physically) shadows? To answer this question, it should be considered that the luminance patterns giving rise to the impossible shadows are extremely rare in nature; and that they can be found only as a matter of coincidence when an illumination edge exactly overlaps a reflectance one. Perhaps, it was more economic, in evolutionary terms, for a system to follow a simply rule (like that one above proposed) rather than spending resources in developing a system able to recognise a violation to this rule, which occurs very rarely in natural conditions. In any case, a study of this nature is beyond the remits of our concerns here, but would make for fascinating reading elsewhere.

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