The Luminance Misattribution in Lightness Perception

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The Simultaneous Lightness Contrast is the condition whereby a grey patch on a dark background appears lighter than a physically identical patch on a light background. This is probably the most studied phenomenon in lightness perception. Although this phenomenon has been explained in terms of low-level mechanisms, convincing evidences supporting a high-level interpretation have been presented over the last decades. Two are the main high-level interpretations. On one side, the layer approach claims that the visual system splits the luminance into separate overlapping layers, corresponding to separate physical contributions; whilst on the other side, the framework approach maintains that the visual system groups the luminance within a set of contiguous frameworks. One of the biggest weaknesses of the layer approach is that it cannot account properly for errors in lightness perception (Gilchrist, 2005 Current Biology, 15(9), 330–332). To extend the multiple layers interpretation to errors in lightness perception, in this study we show that the perceptual lightness difference among equal patches on different backgrounds increases even when the luminance contrast with their backgrounds shrinks. Specifically, it is shown that the perceptual lightness difference among equal patches on different backgrounds intensifies when a small-sized semi-transparent surface is interposed between the patches and the backgrounds. This result indicates that in these conditions the visual system besides decomposing the luminance into separate layers also becomes liable for a luminance misattribution. It is proposed that the photometric and geometric relationships among the luminance edges in the image might account for this misattribution.

Key words: Luminance misattribution, Framework schema, Multilayer schema, Luminance edges.

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The Simultaneous Lightness Contrast (SLC) is the condition whereby a grey patch on a dark background appears lighter than an equal patch on a light background (Figure 1).

![Figure 1. The Simultaneous Lightness Contrast. The grey patch on the dark background appears lighter than the equal patch on a light background.](image)

This phenomenon has been a focus of centuries of debate that has interested scientists and philosophers since Aristotle’s time (Wade, 1996). In the 19th century a rage of controversy busted between Hering (1874/1964) supporting a low-level explanation based on processes sensitive to contrast, and Helmholtz (1866) in favor of an explanation based on high-level processes involving assumptions about the configuration as a whole.

The low-level explanation was particularly in vogue during the sixties mainly because of the physiological discovery of the lateral inhibition process in the limulus retina (Hartline, Wagner and Ratliff, 1956). In order to attempt for the SLC phenomenon, the low-level approach claims that the receptors stimulated by the light background send inhibition to the receptors stimulated by the patch that the background surrounds, causing perceptual darkening; while, the receptors stimulated by the dark background sends little inhibition to nearby receptors and, therefore, there is not a darkening effect (Cornsweet, 1970).

During the last few decades, however, the balance has been shifted towards more high-levels theories. This is because a series of visual illusions have been presented that directly contradict a retinal interactions explanation (e.g. Knill and Kersten, 1991; Adelson, 1993; Agostini, and Proftt, 1993; Agostini. and Galmonte, 2002). Indeed, although with some exceptions (for example, Kingdom and Moulden, 1992; Todorović, 2006) many lightness theorists have now accepted the viewpoint that the retinal image is decomposed into separate components. Agreement amongst scientists, however, is still far from being achieved. Nowadays the debate is between the “framework” and the “layer” type of decomposition schemes.
The framework decomposition schema (also referred as “mid-level” approach) claims that the visual system divides an image into frameworks, or contiguous regions of illumination or shadow, like states on a map. In such models (see, for example, Gilchrist et al., 1999; Adelson, 2000; Bressan, 2006), the perceived lightness of any given surface depends mainly on its photometric relationships with the other surfaces in the same framework. The more one framework is perceptually segregated from the others; the more the perceptual lightness of the surfaces within that framework is computed independently from the surfaces outside the framework. Hence, the SLC phenomenon should occur because the equal grey patches are grouped within different frameworks, and their perceptual lightness is computed – partially – independently from each other.

The layer decomposition schema, on the other hand, claims that the visual system decomposes the pattern of light intensities reaching the eyes into separate overlapping layers, corresponding to separate physical contributions: One layer corresponds to the reflectance, one other to the illumination and so on (Musatti, 1953; Metelli, 1974; Bergstrom, 1977; Barrow and Tenenbaum, 1978; Anderson, 1997; Ekroll et al, 2002; Eagleman, Jacobson and Sejnowski, 2004). According to this schema, the SLC phenomenon should occur because of an error in the layer decomposition process (i.e. a luminance misattribution; Soranzo and Agostini, 2004; 2006a; 2006b). It means that part of the luminance of the patch lying on the light background that should have been attributed to its reflectance, is attributed to the illumination and that part of the luminance of the patch lying on the dark background that should have been attributed to the illumination, is attributed to its reflectance.

Although errors in lightness perception can be accounted for by the luminance misattribution luminance, sustainers of the framework decomposition schema claim that “such efforts to model the errors have not proven very effective” (Gilchrist, 2005; page 322).

The aim of the present research is to provide evidence that the visual system does split the luminance in a multi layer structure and that a luminance misattribution occurs at some stage of this process. In order to achieve this aim, a new illusion is presented here, showing that the magnitude of the SLC phenomenon is enhanced when a semi-transparent surface is interposed between the grey patches and the backgrounds\(^1\). The new phenomenon is pictured on Figure 2 where the same display of Figure 1 is used, but one small sized semi-transparent surface is interposed between the grey patches and the backgrounds.

\(^1\) This is different from the “tissue-contrast phenomenon” (Helmholtz, 1866; page 276 and Beck, 1972; page 41) in which the semi-transparent surface is superimposed to the patches – the interposition of the semi-transparent surface does not alter the patches luminance.
As can be observed, the perceptual lightness difference between the grey patches undergoes a substantial enhancement compared to that in Figure 1, in spite of the fact that, lying on the same semi-transparent surface, their atmospheric conditions are more similar in this new state.

This new illusion seems to challenge the framework decomposition schema because the semi-transparent surface creates a new framework on to which both the patches belong. As the two patches belong (at least partially) to the same framework, their lightness should be more similar. But this does not seem what actually happens.

This illusion, however, is in line with the layer decomposition schema and might be due to a luminance misattribution. Indeed, the effect might be due to the relationship between the covered and uncovered fractions of the edge between the backgrounds. When two collinear luminance edges – one including the other – share the same polarity, increasing the ratio at the including one enhances the perception that they are portions of an illumination edge (Singh and Anderson, 2002; Soranzo and Agostini, 2004; Soranzo, Galmonte and Agostini, 2009). This misinterpretation of the luminance edges may induce the visual system to attribute differently for the two patches the luminance to the illumination and to the lightness. The grey patch on the light background might be perceived on a more intensively illuminated field rather than the other patch.

According to this line of reasoning, the enhancement of the SLC effect should vanish if the interposed semi-transparent surface does not rearrange the luminance edges of the display. Figure 3 shows that this is what seems to happen: When the vertical dimension of the semi-transparent surface is increased, in order that the two luminance edges between the backgrounds are not generated, the magnitude of the SLC does not seem to enhance compared to the condition.
without the semi-transparent surface. On the contrary, the two grey patches appear more similar in this new condition.

Figure 3. As a difference from figure 2, the semi-transparent surface vertical dimension is enlarged in order to overlap entirely both the backgrounds. The lightness difference between the grey patches does not seem to enhance compared to that one in Figure 1.

To sum up, according to the layer decomposition schema the SLC in figure 1 might be due to a relatively small luminance misattribution. In this case the two grey patches are separated by one luminance edge only, with a given polarity, and the visual system should partially misinterpret this edge as an illumination edge (which most illuminated side depends on its polarity). This should lead to a small misattribution. However, the interposition of small semi transparent surface strengths this misinterpretation because in this condition there are two collinear luminance edges sharing the same polarity\(^2\). When, instead, the vertical dimension of the interposed semi-transparent surface is increased, to prevent the formation of two collinear edges sharing the same polarity, then the two grey patches are separated by one luminance edge only, like in the SLC display. Because of this, the illusion magnitude should not increase in comparison to the SLC display. On the contrary, as the luminance ratio at this edge is now reduced, the patches should appear as lying in a more similar illumination conditions, leading to a reduction of the illusion magnitude.

EXPERIMENT

To test the hypothesis that interposing a semi-transparent surface between the patches and the backgrounds in the SLC display enhances the perceived

\(^2\) On this topic, we have shown that by violating either the polarity or the collinearity of luminance edges, the SLC illusion magnitude reduces (Soranzo, Galmonte and Agostini, 2009).
lightness difference between the patches, and that this effect depends on the vertical dimension of the semi-transparent surface, a double lightness matching experiment was run. The SLC display was used as a baseline, while in the experimental conditions a semi-transparent surface, which vertical dimension was systematically manipulated, was interposed between the patches and the backgrounds.

**Method**

*Observers.* Ten volunteer observers, students from the University of Teesside, participated to the experiment. All had normal or corrected-to-normal acuity and were naïve with regard to the experimental design.

*Apparatus and stimuli.* The displays hanged on a wall of a room, which illumination level was controlled. Two equal grey patches placed on a light and dark background respectively constituted the baseline, that was build as follow. In the centre of each of two adjacent square-shaped backgrounds (opaque 244.56 g/m² paper, 13x13 cm; 45.05 cd/m² and 2.11 cd/m², respectively; corresponding to 9.5 and 2.1 Munsell unit) placed on a homogeneous surround (opaque 244.56 g/m² paper, 21x30 cm; 33.01 cd/m², corresponding to 8.3 Munsell units), a smaller square-shaped patch (opaque 244.56 g/m² paper, 2.5x2.5 cm, 19.6 cd/m², corresponding to 6.6 Munsell unit) was glued.

In the experimental conditions, a semi-transparent surface (a matte frosted acetate paper, 0.175 mm thick) was attached in the centre of the two backgrounds. Its width was 26 cm (i.e. it matches the width of the two backgrounds) whilst its vertical dimension varied among four levels: 13, 10, 6.5 and 4 cm. In this way, the percentage of uncovered edge between the backgrounds was 0%, 33%, 50% and 70%, respectively. The luminance values of the portion of the semi-transparent surface lying on the light and dark background were 23.10 cd/m² and 4.08 cd/m², respectively. In the experimental conditions, the small square-shaped patches were glued on the top of the semi-transparent surface rather than on the backgrounds as in the baseline. In this way, the patches luminance was the same in all the conditions.

A set of twelve 1/2 Munsell spaced achromatic reference-chips placed above the display served for the double lightness matches. The size of each reference-chip was 1.5x1.5 cm and they were placed on a chessboard-type background. The squares shaping the chessboard had the same reflectance of the light and dark background. Figure 4 is a picture of the experimental condition where the ratio between the semi-transparent surface and the backgrounds vertical dimension was 50%.

**Procedure**

The observers set in a normally illuminated room at a distance of one meter from the hanging displays (so that the whole display size was 12x16.4 deg). They were instructed to rate the lightness of both the grey square-shaped patches against the Munsell reference-scale. Specifically, observers were asked to choose from the Munsell reference-scale, one chip matching the perceived lightness of the patch on the dark background and another chip matching the perceived lightness of the other patch. The observers performed four matches for each of the five stimuli presented in random order, so they provided forty lightness estimations (5 displays x 2 matches per display x 4 repetitions). They had all the time needed to produce the matches. After registering the participants’
ratings, the experimenter changed the display and the next trial began. The whole session lasted about fifteen minutes.

**Results and discussion**

Figure 5 shows the results of the experiment. Mean ratings are expressed as the difference between the Munsell value assigned by the observers to the patches minus the objective value (6.6/). A repeated measure ANOVA with the vertical dimension of the interposed semi-transparent surface and the background intensity as independent variables was run on the transformed ratings. It emerged a significant effect of both the variables \( F(4,36) = 3.59; p < 0.05 \) and \( F(1,9) = 65.14; p < 0.01 \), respectively. The interaction between the variables was also significant \( F(4,36) = 19.15; p < 0.01 \).

As can be seen from the graph; the lightness of the patch on the dark background increases while the vertical dimension of the interposed semi-transparent surface reduces. Conversely, the lightness of the patch on the light background decreases while the vertical dimension of the interposed semi-transparent surface reduces. However, the strength of the effect is asymmetric. The lightening effect of the semi-transparent surface on the lightness of the patch

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*Figure 4. Picture of one experimental condition. The ratio between the semi-transparent surface and the backgrounds vertical dimension is 50%.*
on the dark background is greater rather than its darkening effect on the patch on
the light background. The effect sizes were $\varepsilon^2 = 0.37$ and $\varepsilon^2 = 0.20$ for the patch
on the dark and light background, respectively.

Figure 5. Results of the experiment for the patch on the light and dark background. Mean
ratings are expressed as the difference between the Munsell value assigned by the observers
minus the objective value (6.6/). Bars indicate standard errors.

**Illusion magnitude.** Figure 6 shows the magnitude of the illusion in comparison
to the baseline. Mean ratings are expressed as the difference between the Munsell value assigned by the observers to the patch on the dark and light background in
the experimental conditions minus the same difference reported for the baseline.
Therefore, the zero corresponds to the perceived lightness difference between
the grey patches in the baseline. The averaged difference between the observers’
perceived lightness for the grey square-shaped patches in the baseline was equal
to 0.75 Munsell units, whilst this difference enhanced to 2.6 Munsell units in
the 70% condition, leading to an improvement of the magnitude of the SLC
phenomenon by a factor of 3.46.

A repeated measure one way ANOVA showed a significant effect of
the vertical dimension of the interposed semi-transparent surface [$F_{(3,9)} = 64.58;
p.<0.01$]. A last square means analysis reveals a significant difference ($p. <0.01$)
among all the comparisons but 33% vs. 50% ($p. = 0.28$).
Figure 6. Results of the experiment on the magnitude of the effect. Mean ratings are expressed as the difference between the Munsell value assigned by the observers to the patch on the dark and light background in the experimental conditions minus the same difference reported for the baseline. Bars indicate standard errors.

As can be observed from the graph, with respect to the baseline, the SLC phenomenon is enhanced by the interposed semi-transparent surface only when a fraction of the edge between the backgrounds remains uncovered. A further reduction of the semi-transparent surface vertical dimension yields to an additional increase of the effect. However, when the whole edge is covered by the semi-transparent surfaces, the SLC phenomenon shrinks.

DISCUSSION

Outcomes of the present research show that the magnitude of the SLC phenomenon increases when a small sized semi-transparent surface is interposed between the grey patches and the backgrounds. Furthermore, this effect seems to be modulated by the vertical dimension of the semi-transparent surface. When it covers entirely the edge between the backgrounds, the lightness difference
between the grey patches decreases compared to the baseline. Conversely, when the vertical dimension of the semi-transparent surface is reduced in order to leave uncovered a fraction of the edge between the backgrounds; the magnitude of the SLC phenomenon increases and a further reduction of its vertical dimension yields to an additional increase of the effect.

This new illusion seems to challenge the low-level interpretation because the luminance contrast between the grey patches and their backgrounds is reduced by the semi-transparent surface. Therefore, the dissimilarity in the neuronal inhibition activity should reduce too; and this should lead to a reduction of the magnitude of the SLC effect. However, this happens only when the semi-transparent surface overlaps entirely the edge between the backgrounds.

This new illusion seems to challenge also the framework decomposition schema. This is because the semi-transparent surface leaving uncovered part of the display creates a new framework on to which both the patches, at least partially, should belong. As can be seen in figure 4, the inserted semi-transparent surface is clearly seen as a separate layer of different material, giving rise to a new framework where both the grey patches ly. Because of this, the semi-transparent surface should increase the perceptual belongingness between the patches themselves causing their perceived lightness to be computed more coherently, leading to a reduction of the magnitude of the SLC phenomenon, not to an increase.

However, the enhancement of the magnitude of the SLC effect produced by the interposed semi-transparent surface could be explained in accordance with the layer decomposition schema, stating that the luminance of the two patches is differently attributed to the reflectance and to the illumination. To explain why, compared to the baseline, the luminance misattribution enhances when a small-sized semi-transparent surface is interposed between the patches and the background of the SLC display, we suggest considering the relationship among the luminance edges in the image. In particular, the enhancement of the luminance misattribution might be due to the relationship between the covered and uncovered fractions of the edge between the backgrounds. When two collinear luminance edges – one including the other – share the same polarity, increasing the ratio at the including one enhances the perception that they are portions of an illumination edge (Singh and Anderson, 2002; Soranzo and Agostini, 2004; Soranzo, Galmonte, Agostini, 2009). This misinterpretation of the luminance edges may induce the visual system to attribute differently for the two patches the luminance to the illumination and to the lightness. Part of the patch on the light background luminance that should have been attributed to its lightness is attributed to the illumination; and part of the patch on the dark background luminance that should have been attributed to the apparent illumination is attributed to the lightness. This is what we call the “luminance misattribution”.
This may also explain why the SLC illusion is weaker without the small sized semi-transparent surface and why it reduces further when the semi-transparent layer overlaps the entire length of the edge between the backgrounds. In the SLC illusion, indeed, the two grey patches are separated by one luminance edge only, with a given polarity, and the visual system should still misinterpret this edge as an illumination edge (which most illuminated side depends on its polarity), but this misinterpretation arises from one luminance edge only (i.e. it is not supported by an additional collinear edge sharing the same polarity). In the SLC with the interposed semi-transparent surface covering the whole edge between the backgrounds, the two grey patches are again separated by one luminance edge only, like in the SLC display without semi-transparent layer. However, as the luminance ratio at this edge is now reduced compared to the SLC display without semi-transparent layer, the patches should appear as lying in a more similar illumination conditions, leading to a reduction of the illusion magnitude.

Finally, the suggestion that the illusion may originate from the fact that, at some stage of the visual process, the luminance edge between the patches is erroneously interpreted as an illumination edge, is further supported by the illusion asymmetry. Indeed, the lightning effect of the small-sized semi-transparent surface on the patch on the dark background is stronger rather than its darkening effect on the patch on the light background (see figure 5). This asymmetry in the pattern of errors is congruent to that one occurring when two luminances are crossed by an illumination edge. Zdravković, Economou and Gilchrist (2006), for example, found that, when the illumination fields sizes are equal, the perceived lightness of the shaded side of an object is more error susceptible rather then the illuminated side.

Summarizing, outcomes of the present research are consistent with the hypothesis that the visual system does decompose the luminance into separate layers; during this decomposition process it might become liable for a luminance misattribution, which may account for errors in lightness perception. Moreover, results show that the luminance misattribution might depend on the photometric and geometric relationships among the luminance edges visual scene, supporting the layer decomposition interpretation of lightness perception.

REFERENCES


3 It should be noted that authors’ empirical findings can be explained also by the framework decomposition schema, but this does not alter our line of reasoning.


