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The effects of belongingness on the Simultaneous Lightness Contrast: a Virtual Reality study

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Abstract

Simultaneous Lightness Contrast (SLC) is the phenomenon whereby a grey patch on a dark background appears lighter than an equal patch on a light background. Interestingly, the lightness difference between these patches undergoes substantial augmentation when the two backgrounds are patterned, thereby forming the articulated-SLC display. There are two main interpretations of these phenomena: The mid-level interpretation maintains that the visual system groups the luminance within a set of contiguous frameworks, whilst the high-level one claims that the visual system splits the luminance into separate overlapping layers corresponding to separate physical contributions. This research aimed to test these two interpretations by systematically manipulating the viewing distance and the horizontal distance between the backgrounds of both the articulated and plain SLC displays. An immersive 3D Virtual Reality system was employed to reproduce identical alignment and distances, as well as isolating participants from interfering luminance. Results showed that reducing the viewing distance resulted in increased contrast in both the plain- and articulated-SLC displays and that, increasing the horizontal distance between the backgrounds resulted in decreased contrast in the articulated condition but increased contrast in the plain condition. These results suggest that a comprehensive lightness theory should combine the two interpretations.

Keywords:

Lightness perception, Simultaneous Lightness Contrast, Anchoring Theory, Layer decomposition process, Virtual Reality, Perceptual belongingness.

1. Introduction

Simultaneous Lightness Contrast (SLC) is the phenomenon whereby a grey patch on a dark background appears lighter than an equal patch on a light background (see Fig. 1).

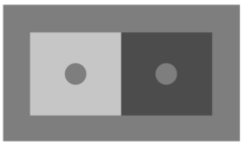

Figure 1. The Simultaneous Lightness Contrast (SLC) display. The grey patch on the dark background appears lighter than the equal patch on the light background.

Interestingly, the perceived lightness difference between the two grey patches increases when the plain backgrounds are replaced with patterned ones - thereby shaping the *articulated-SLC* display (Fig. 2). According to Adelson (2000) the enhancement of the contrast effect occurs even when the geometric luminance average of the backgrounds remains the same for both the plain and articulated displays.

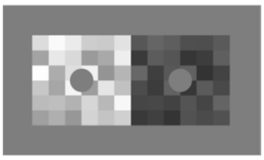

Figure 2. The perceived lightness difference between the grey patches increases when the plain backgrounds shown in Fig. 1 are replaced with patterned ones.

It is important to note that when the backgrounds share the same average intensity in both the plain and articulated displays, retinal receptor stimulation is the same for both conditions. This evidence challenges an interpretation based on low-level factors (see also Economou, Zdravkovic & Gilchrist, 2007). Indeed, apart from some exceptions (for example, Kingdom & Moulden, 1992; Todorović, 2006) most lightness theorists accept that these phenomena do not originate at the retinal level but instead occur at a later stage of the visual process. However, there is still no shared consensus among scientists; and the debate is now between those who attribute these phenomena to mid-level processes and those who attribute them to high level processes.

1.1 Mid-level theories

Although maintaining that lightness phenomena do not occur at the retinal level, the mid-level approach asserts that they are derived directly from luminance and that the perceived lightness of any surface depends on its photometric and geometrical relationships with the other surfaces in the same perceptual group (Gilchrist, 2006). The most popular model within this approach is Anchoring Theory (AT), advocated by Gilchrist et al. in 1999. According to AT, lightness perception derives from a two-dimensional decomposition of the luminance in frameworks, which are defined in terms of Gestalt grouping principles. Specifically, frameworks are a “group of surfaces that belong to each other, more or less” (Gilchrist et al., 1999; p. 804).

There are two types of framework: “the largest framework consists of the entire visual field and is called the *global framework*; subordinate frameworks are called *local frameworks*” (Gilchrist et al., 1999; p. 804).

It is claimed that the visual system assigns the value of white to the highest luminance within each local framework (local anchor), whilst the lightness of the other surfaces is derived as a ratio between their luminance and that of the local anchor. However, the net lightness values also depend on the highest luminance in the visual scene (global anchor); hence, the final lightness of each surface will be the weighted sum of the value that it has received locally plus the value that it has received globally. In other words, the lightness of a surface is *co-determined* by its luminance ratio with the local anchor and its luminance ratio with the global anchor. In addition, AT includes a second, competing “Area rule”, stating that the larger area tends to be perceived as white and serves as an anchor for the other surfaces’ lightness. The actual anchor is a compromise between the highest luminance and largest area rules. Whilst this second rule is important, it is not directly relevant in the current project.

According to AT, the equal grey patches in the *plain-SLC* display are grouped into two different local frameworks with each one consisting of one patch and its bordering background. Having the highest luminance in the display, the light background is the global anchor. Both patches are assigned identical grey values relative to the global anchor; however, the local lightness assignments are different. Whilst the patch on the light background still receives the same grey value it receives globally, the patch on the dark background, having the highest luminance within its local framework, receives the local value of white. Thus, the *plain-SLC* should occur because the patch on the dark background lightens in comparison to the other patch. In addition, it is maintained that a “scale normalization effect” (Gilchrist et al., 1999; p. 813) may slightly contribute to this phenomenon. Specifically, as each of the local frameworks consists of a limited luminance range, the lightness values are slightly expanded. In practice, this implies that the grey patch on the light background undergoes a modest darkening effect.

Within this interpretative schema, in the *articulated-SLC* the contrast magnitude increases in comparison to the plain condition for two reasons: First, articulation strengthens anchoring within each local framework; that is, articulation increases the weight of the local framework. Whilst this mechanism does not affect the lightness of the patch on the light background (its lightness is a compromise between two equal values); it generates a further perceptual lightening of the patch on the dark background (its lightness is now more affected by its local white value rather than by its global grey value). Second, the global anchor has now a higher luminance value: to maintain the same luminance mean, some patches shaping the light background in the *articulated*-SLC display must have a higher luminance value than the plain light background. This leads to a darkening effect of the patch on the light background. Indeed, although increasing the luminance of the global anchor darkens both the patches, as the weight of the local framework is higher in the articulated condition, the patch on the light background is more affected by this luminance enhancement (Bressan & Actis-Grosso, 2006).

A modified version of this model has been advanced by Bressan (2006) who promoted Double Anchoring Theory (DAT). The main difference between AT and DAT is that the latter includes an additional anchor which is the *surround-as-white* anchor. Namely, it proposes that: "within each framework, the lightness of the target region is determined not only by its luminance ratio to the highest luminance (HL step) but also by its luminance ratio to the surround luminance (surround step). Because they are anchors, highest luminance and surround luminance are defined as white" (Bressan, 2006; p. 529).

This model explains both the *plain-SLC* and the *articulated*-SLC in a similar way to the anchoring model with the important difference that, by including a surround rule, it also explains the double increment version of the SLC, which is the condition whereby both of the grey patches have a higher luminance value than that of their backgrounds.

Another lightness model which can be included within the mid-level category has been suggested by Adelson (2000). This model is based on the concepts of *atmosphere* and *adaptive windows*. An atmosphere is a region of the visual field sharing the same illumination, glare or fog. Each window has its own atmosphere, and lightness estimates are computed based on statistical and configural information within the adaptive window. The window is adaptive because its size changes as a function of the number of surfaces in a given area of the image. A larger number of samples will lead to better estimates of the lightness values. However, the visual system is hindered by enlarging the window too much because the atmosphere varies from place to place in the image; thus, there is also a counterargument in favour of small windows.

The model predicts, therefore, that the window grows when there are too few samples, and shrinks when there are many. According to this interpretative schema, since there are only a few large surfaces in the *plain-SLC* the window tends to grow, becoming so large that the statistics surrounding either of the grey patches are very similar. As a result, the lightness difference between the grey patches is rather small. Conversely, in the *articulated-SLC* each window remains fairly small and does not mix statistics from different atmospheres, so the lightness difference between the grey patches is bigger.

1.2 High-level theories

In contrast to the mid-level approach, the high-level approach postulates that the visual system does not use photometric and geometrical luminance relationships to compute lightness values directly. Rather, it utilises these relationships to split the luminance into separate overlapping layers, which correspond to separate physical contributions: one layer for the reflectance, another for the illumination, another for transparency and so on. Some minor differences notwithstanding, many theories and models can be put together within this schema (Musatti, 1953; Metelli, 1974; Bergström, 1977; 1994; Barrow & Tenenbaum, 1978; Gilchrist, 1979; 1988; Gilchrist & Jacobsen, 1983; Gilchrist, Delman & Jacobsen (1983); Adelson & Pentland, 1996; Anderson, 1997; Eagleman, Jacobson & Sejnowski, 2004; and others).

A prototype model of the high-level approach was advocated by Bergström in 1977. The author suggested a vector model of lightness perception, attempting to apply Johanson's (1950; 1958; 1964; 1975) perceptual vector analysis. This model postulates that the light reflected by illuminated surfaces is automatically analysed into common and relative components. The visual system is assumed to be able to distinguish between the illumination component and the reflectance component in the proximal stimulus. This distinction is made possible by the fact that illumination is a common component. "This assumption (the commonality assumption) means that the visual system can discriminate between the retinal projection of an illumination border and that of a reflectance border and between the retinal projection of a shadow and that of a darker colour because illumination has this characteristic of being a common component" (Bergström, 1994; p. 257).

To account for the *plain-SLC* phenomenon, the two backgrounds are supposed to be the main determinant of the common component of illumination. As the common component is different for the two grey patches (which, in turn, constitute the relative component) they are perceived to be under different illuminations.

Within the same paradigm, it has been proposed that the edge between the two backgrounds of the SLC display may be perceived partially as an illumination edge, rather than a pure reflectance edge (Gilchrist, 1988; Schirillo, 1999a, b). Because of this, as the two greys share the same luminance but are perceived as being under different illuminations, they appear different in lightness. In other words, a "luminance misattribution" (Soranzo & Agostini, 2004, 2006a, 2006b) occurs: part of the luminance of the patch on the light background that should have been attributed to its lightness is attributed to its apparent illumination and/or part of the luminance of the patch on the dark background that should have been attributed to its apparent illumination is, instead, attributed to its lightness.

According to Schirillo (1999a, b) the enhancement of the effect in the *articulated-SLC* occurs because "adding articulation to the surrounds [...] increases the inference that the edge between the two surrounds is an illumination edge" (Schirillo, 1999a; p. 805). Soranzo & Agostini (2006a) remarked that when both the backgrounds are articulated, there are many different luminance pairs with the same polarity and the visual system "[...] uses this information to infer the illumination intensity" (Soranzo & Agostini, 2006a; p. 112). Where luminance pairs refer to those adjacent squares that straddle the border between backgrounds and polarity refers to the fact that the direction of the luminance change is consistent, for example moving from light on the left to dark on the right. According to this suggestion, in the articulated condition the inference that the edge between the two backgrounds is an illumination edge is supported by the fact that this edge is generated by many luminance pairs with the same polarity; whilst in the plain condition it is generated by only one luminance pair.

Soranzo & Agostini (2006a, b) also suggested that the perception of two different illuminations increases when the perceptual belongingness between the luminance pairs with the same polarity is increased (where perceptual belongingness refers to the grouping of a set of apparent elements into a perceived whole; Wertheimer 1923/1938).

1.3. Testing mid- and high-level theories

Although emphasizing different visual mechanisms, both the mid- and high-level theories are able to account for both the plain-SLC phenomenon and the strengthening of contrast that occurs when the backgrounds are articulated.

In addition, the two theories also suggest that contrast should increase further if the viewing distance from the SLC displays is reduced. This is because reducing the viewing distance causes the display to cover a larger area of the overall visual field. According to the mid-level approach, this should increase the segregation between the display and the larger framework. Because of this increased segregation, lightness values should be less affected by the global anchor in the larger framework but more influenced by the local anchor (Gilchrist et al. 1999). According to the high-level approach, the larger the surrounding field is, the smaller the difference between the common component and the luminance level of the surround (Bergström, 1977). This is represented graphically in Figure 3.

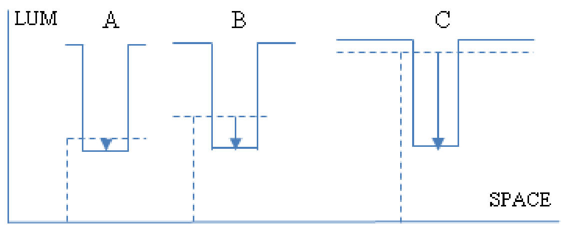

Figure 3. The assumed shift of the common component (------) as a function of the size of the surrounding field. Adapted from Bergström (1977, page 185)

Interestingly, Bergström (1977) considered the effects of area on the SLC as major evidence in support of his model, as some studies had found that increasing the area of the SLC display strengthens the contrast (e.g. Yund & Armington, 1975). However, not all findings have been consistent: earlier research by Burgh & Grindley (1962) failed to find any effect of SLC display area on contrast. Furthermore, contrary to other studies that have examined the contrast phenomenon, Yund & Armington (1975) tested the effects of the darker region on the brighter; an approach which has limited utility, since contrast effects are primarily effects of a brighter region on the perception of the darker region, not the other way around.

Thus, further examination of the effects of manipulating the area of the SLC display on contrast is necessary.

The first aim of this project was to test the mid- and high-level predictions on the effects of viewing distance of both the *plain*- and *articulated-SLC* displays. To enhance the perceptual effects of viewing distance this project utilized a Virtual Reality (VR) cave. This system allowed for precise manipulation of the vergence-accommodation distance by maintaining luminance intensities at a constant level.

The second aim of this project was to contrast the mid- and high-level theories by manipulating the horizontal distance between the two backgrounds that form the *plain*- and *articulated-SLC* displays. The predictions of the mid- and high-level theories regarding the effect of this manipulation are different:

- According to mid-level theories, separating the backgrounds should increase the contrast magnitude in both the plain- and articulated-SLC. This is because this display manipulation should increase the segregation of the two frameworks, which should weaken the global framework, or equivalently, increase the weight of the local frameworks, leading to a further lightening of the patch on the darker background.
- According to the high-level theories, separating the backgrounds should have a different effect, depending on the SLC display type:
    - Contrast should <u>strongly decrease</u> in the *articulated-SLC* display; this is because the belongingness factor of proximity between the luminance pairs with the same polarity is reduced and this should reduce the inference that the edge between the two backgrounds is an illumination edge. This reduction should be proportional to the distance between the backgrounds. Increasing the distance should proportionally reduce the proximity between the luminance pairs with the same polarity.
    - Contrast should only <u>marginally decrease</u> in the *plain-SLC* display. While the belongingness factor of proximity between the luminance pairs with the same polarity is reduced in the same way as in the articulated display, the magnitude of the effect is not as strong here, due to the fact that there is only one luminance pair involved.

Figure 4 graphically represents these predictions.

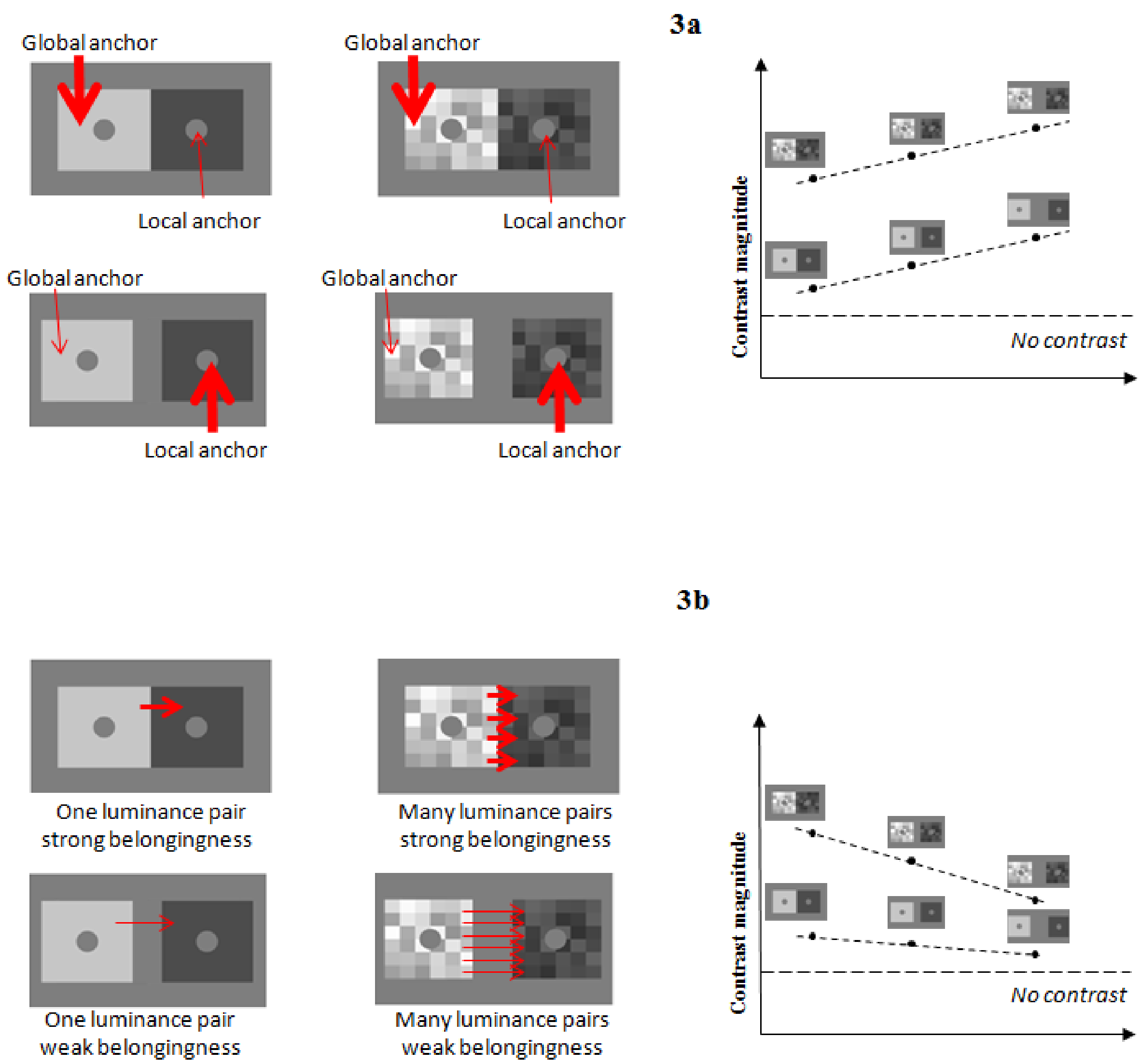

Figure 4. a) According to mid-level theories, separating the backgrounds should increase the weight of the local anchor: contrast should increase in both SLC displays. The thickness of the arrows represents the influence of the anchors. The graph on the right depicts the expected results.

4.b) According to high-level theories, separating the backgrounds should reduce the belongingness between luminance pairs with same polarity: contrast should strongly decrease in the *articulated-SLC* and should only marginally decrease in the *plain*-SLC. Thickness of the arrows represents the strength of belongingness. The graph on the right depicts the expected results.

2. EXPERIMENT

To achieve the project aims, both the *plain*- and *articulated*-SLC displays were used. The following variables were systematically manipulated: i) the type of background; ii) distance between the observers' eyes and the display; and iii) the horizontal distance between the backgrounds.

The project employed an immersive 3D virtual environment (a VR cave) to present the experimental stimuli. While a number of perception phenomena have been studied with virtual environments (Wolff & Zettegren, 2002; Wolff, 2003, 2007; Ware et al., 1999; O' Sullivan & Dingliana, 2001; O'Sullivan & Lee, 2004; O'Sullivan et al., 2003; Reitsma & O'Sullivan, 2008), very little work has been specifically dedicated to lightness perception. Nevertheless, this technology has a number of advantages over computer or paper experiments. The VR cave provides precise control over the environment for each participant, to a degree that is extremely difficult to achieve by manipulating physical objects in a room. Most importantly, it allows full control of the luminance and of the spatial arrangement of the surfaces in the visual scene. This might be relevant when studying perceptual belongingness factors. As Gilchrist et al. (1999) explained "When the [SLC] display is presented in a textbook, it is perceived to belong to the page of the book and to the table on which the book is lying. Thus, […] the illusion should be quite weak" (p. 814). Adopting a VR technology prevents surfaces from outside of the experimental display from affecting the experimental examination of the SLC phenomenon.

2.1 Material and methods

2.1.1 Observers

Fifteen participants took part in the experiment, all of whom were students and staff from Teesside University. All participants had normal or corrected-to-normal acuity and were naïve with regard to the experimental design.

2.1.2 Apparatus and stimuli

An ad-hoc virtual environment was created and displayed under an immersive 3D setting (a 4-screens CAVE™-like stereoscopic display [Cruz-Neira et al. 1993]). The immersive 3D VR system was composed of both an immersive hardware platform (large surrounding screens within a cubic-shape of 3.0×3.0×2.25 meters), and a software component responsible for the 3D visualisation of the virtual environment (see Fig. 5). The 3D visualisation was supported by the Unreal™ game engine 2.0, which was upgraded with a multi-screen controller supporting stereoscopic visualization and head motion tracking (see Cavazza et al., 2007; Lugrin et al., 2010).

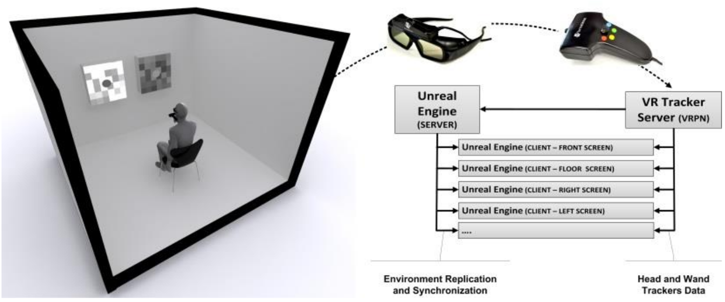

Figure 5: Sketch of the immersive 3D VR system adopted in the experiment.

Within the immersive system, depth perception was elicited through a combination of binocular stereopsis and head motion parallax. This enabled the reproduction of real life depth perception (Jones et al., 2008; Hassaine et al., 2010). The SLC displays were mapped on the surfaces of two virtual objects which were always facing the participant at a configurable distance (see Fig. 5). The VR system rendered these virtual objects in stereopsis while constantly adjusting their perspectives to exactly match the participant's head position and direction inside the CAVE™. The system duplicated each virtual object with a right-eye and left-eye version under two different perspective points, each being separated by a distance equal to 6 cm (the average human interpupillary distance). The right and left views projection were then alternated at high frequency (120Hz) and synchronised with shutter glasses, letting the participant perceive only one side at a time. The real-time head tracking in physical space was operated by an Intersense™ IS900 system, while a VRPN (Virtual Reality Peripheral Network) server was used to handle inputs from the head and wand trackers to the game engine (see Fig. 5). Head tracker inputs were then used to adjust the perspective corrections for each screen in real-time, preserving the perception of depth and shared viewpoint between screens. The image rendering process then used the participant's head position to adjust the image perspective, reproducing motion parallax as in real life

The display was arranged as follows: The whole front screen (the larger surround, size 300 x 225 cm) was middle-grey and its luminance, measured behind the goggles, was 26.8 cd/m^2. A grey disc patch (15 cm) served as a *standard* patch and its luminance, measured behind the goggles, was the same as the larger surround (26.8 cd/m^2).

In the plain conditions, two rectangles (the backgrounds, size 50 x50 cm) were drawn in the middle of the larger surround; their luminance was equal to 83.15 cd/m^2 and 8.32 cd/m^2, respectively. The luminance ratio between the two backgrounds was 10:1.

In the articulated conditions, the two plain backgrounds were each replaced by 36 smaller rectangles. The geometric luminance average of each of these two backgrounds was the same as in the plain condition.

Another disc, the *adjustable* patch, with the same dimensions as the standard patch, was drawn on the lighter background and its luminance was randomly assigned by the software at the beginning of each trial. During the experiment, participants were able to adjust its luminance by means of the provided joystick (Fig. 6 shows the two display types).

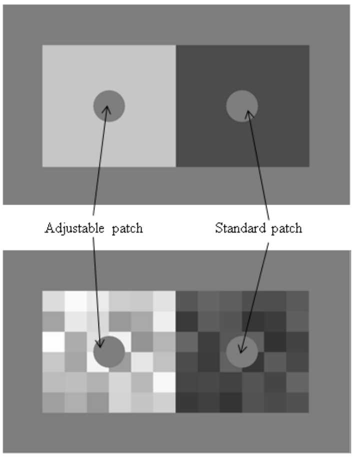

Figure 6. The Plain (top) and Articulated (bottom) SLC displays demonstrating the Adjustable patch on the left and the Standard patch on the right.

By varying the screen parallax, the SLC displays could appear, with respect to the observers' eyes, at three different distances. The parallax could be zero, positive or negative (see Fig. 7):

- In the zero parallax condition, the SLC displays appeared at 255 cm distance from the participants' eyes;
- In the negative parallax condition, the SLC displays appeared at 150 cm distance from the participants' eyes;
- In the positive parallax condition, the SLC displays appeared at 300 cm distance from the participants' eyes.

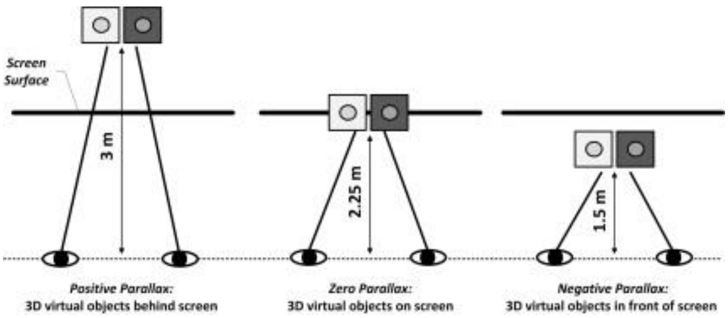

Figure 7. Comparison of the screen parallax settings employed in the experiment.

In this way, the visual angles of the SLC displays varied across the different conditions of the Parallax variable.

In the zero condition each background subtended 11.2°, while both the standard and adjustable patch subtended 3.37°. In the positive condition, each background subtended 19°, while both the standard and adjustable patch subtended 5.7°. In the negative condition, each background subtended 9.5°, while both the standard and adjustable patch subtended 2.9°.
The horizontal distance between the backgrounds shaping the SLC displays (in both the plain and articulated conditions) varied according to the Distance between the backgrounds variable. Their horizontal distance could be 0 meters, 0.2 meters and 0.5 meters.
To sum up, there were 18 experimental displays organised into three independent variables:
1) Type of background (Plain vs. Articulated);
2) Parallax (Zero, Negative and Positive);
3) Horizontal distance between the backgrounds (0 meters, 0.2 meters and 0.5 meters).
Fig. 8 represents a session when the Parallax was positive.

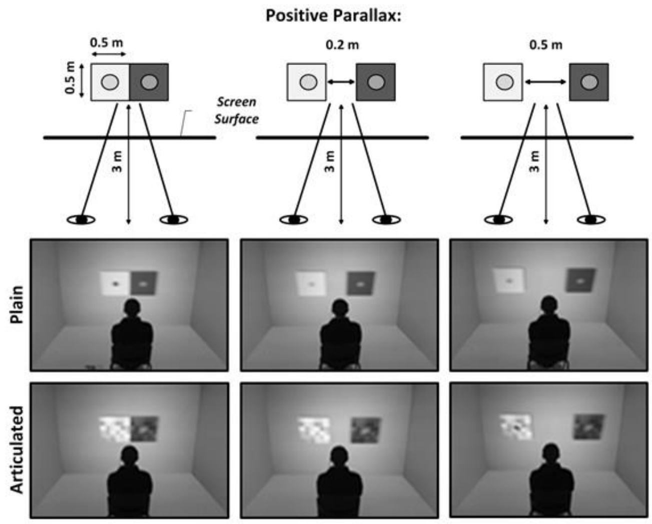

Figure 8. Example of an experimental session. The figure depicts the two levels of the Type of background variable (rows) and the three levels of the Horizontal distance between the backgrounds (columns). In this example the level of the Parallax variable was positive.

2.1.3 Procedure.

Participants were seated in front of the central screen of the CAVE at a distance of 225 cm from the screen. They were instructed to match the luminance of the target patch on the left side to the corresponding standard patch on the right side (see Fig. 5) by using two different keys on the provided controller. The target patch luminance was set to a random value at the beginning of each trial and each display was left on the screen as long as needed for participants to produce the match. When a satisfactory match was achieved, participants pressed a third key on the controller. The target luminance was then recorded and the next trial began. There were 18 stimuli per block and each block was presented 4 times, for a total of 72 trials. The order of the blocks was randomised. The whole experiment lasted approximately 25 minutes.

2.2 Results and discussion

Mean ratings are expressed as the difference - in logarithmic units - between the trimmed mean values assigned by the participants to the target patch in the experimental configurations minus the luminance of the standard patch (26.8 cd/m^2). Observers' mean ratings, together with the standard errors, are shown in Fig. 9.

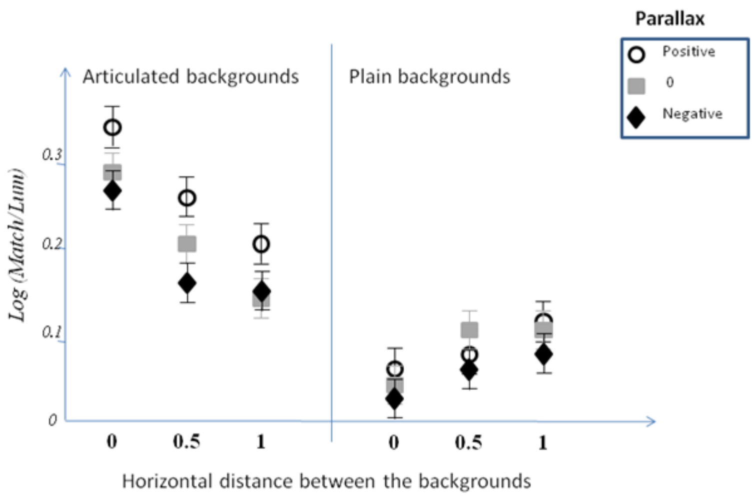

Figure 9. Results of the experiment. Mean ratings are expressed as the difference - in logarithmic units - between the trimmed mean values assigned by the participants to the target patch in the experimental configurations minus the luminance of the standard patch (26.8 cd/m^2).

A Kolmogorov-Smirnov test performed upon the raw data was non-significant; the normality of the data distribution was therefore assumed. A three-way repeated-measures ANOVA, conducted on the transformed data, revealed a significant effect of the three independent variables: Type of background [$F_{(1,14)} = 67.22$; $p < 0.01$]; Parallax [$F_{(1,14)} = 18.16$; $p < 0.01$]; and Horizontal distance between the backgrounds [$F_{(2,28)} = 29.13$; $p < 0.01$]. The interaction between the Type of background and the Horizontal distance between the backgrounds was also statistically significant [$F_{(2,28)} = 13.382$; $p < 0.01$)]. The interactions between the Parallax and the Type of background and between the Parallax and the Horizontal distance between the backgrounds was not statistically significant ($p = 0.28$ and $p = 0.34$, respectively). A least squares means analysis revealed a statistically significant difference at a p level of 0.01 among:

i) The three comparisons between the Horizontal distance between the backgrounds, when the Type of background was Articulated; and
ii) The comparisons between 1 m vs. both 2 and 3 m of the Parallax variable when the Type of background was articulated.

It seems therefore that reducing the distance between the observers' eyes and the SLC displays increased the contrast magnitude in both the *plain-* and *articulated-SLC* displays.

Furthermore, it appears that the manipulation of the Horizontal distance between the backgrounds had different effects according to the display type. When the SLC type of display was articulated, the separation between the backgrounds significantly reduced the perceived difference between the grey patches; and this reduction was proportional to the distance between the backgrounds. Conversely, the same manipulation increased the perceived difference between the grey patches in the *plain-SLC*.

3. Discussion

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. Since the lightness difference between these patches enhances when the plain backgrounds are replaced with patterned ones, it can be accepted that SLC phenomena are not attributable to purely low-level mechanisms. Instead, SLC phenomena can be explained by two different lightness theories, which invoke mid- or high-level visual processes.

Furthermore, although emphasising different visual mechanisms, the mid- and high-level theories each account for both the *plain-* and *articulated-*SLC, while also predicting that contrast should increase by reducing the viewing distance from the SLC display.

The first aim of this project was to test whether the viewing distance does, in fact, affect the contrast magnitude in both the *plain-* and *articulated-SLC* displays. The second aim was to contrast the mid- and high-level theories by systematically manipulating the horizontal distance between the backgrounds of the SLC displays. The two theories make different predictions about the effects of manipulating horizontal distance between the backgrounds: Whilst mid-level theories expect an increase in the contrast magnitude in both the display types; high-level theories expect a strong decrease in contrast in the *articulated-SLC* and only a marginal decrease in the *plain* condition.

To control for intervening variables, a Virtual Reality technology was adopted. This system enabled precise manipulation of the vergence-accommodation distance by maintaining constant luminance intensities. This is particularly important when manipulating the perceptual distance from the experimental displays and between the backgrounds of the SLC displays. Indeed, the effects on lightness of these experimental manipulations are quite feeble (Gilchrist, personal communication). To elicit the effects, it is necessary to run these experiments in more insulated conditions, such as those provided by Virtual Reality caves.

The results showed that i) reducing of the perceived distance between the observers' eyes and the SLC display increased the contrast magnitude for both the display types; and ii) the effects of horizontal separation of the backgrounds were modulated by the SLC display type: this separation reduced the contrast magnitude in the *articulated-SLC* and the reduction was proportional to the distance between the backgrounds. Conversely, it increased the contrast magnitude in the *plain-SLC*. The next sections examine each of these effects separately.

3.1 The effects of the distance between the observers' eyes and the SLC displays (Parallax manipulation)

To test the hypothesis that reducing the viewing distance increases the contrast magnitude in the SLC displays, as predicted by both the mid- and high-level theories, the screen parallax of a VR cave was systematically manipulated. The use of the VR technology allowed for a precise manipulation of viewing distance by preserving the luminance intensities.

Results showed that reducing the viewing distance strengthened the contrast magnitude in both the *plain*- and *articulated-SLC* displays. As anticipated, this result is consistent with both the mid- and high-level theories, as reducing the viewing distance causes the SLC display to cover a larger area of the visual field.

Mid-level theories suggest that enlarging the SLC display area increases the segregation from the larger framework, and lightness values are more influenced by the luminance relationships within the local frameworks (Gilchrist et al. 1999).

High-level theories, on the other hand, enlarging the SLC display area reduces the difference between the common component and the luminance level of the backgrounds (Bergström, 1977). In other words, as the backgrounds are supposed to be the main determinant of the illumination level: the larger their size, the bigger the difference should be in the apparent illumination between them (Bergström, 1977).

To date, there have been few studies conducted into the effects of the area of the SLC display in the literature and these have reported inconsistent results. Burgh & Grindley (1962) found no significant effects; while Yund & Armington (1975) found modest ones. The reason for this may be because the effects of this manipulation are quite weak and the use of an insulated setting, such as that one provided by a VR cave, is necessary for them to emerge.

However, the effects of area in lightness perception have been studied in other lightness domains. In his pioneering investigations on lightness constancy, Katz (1911/1935) found that the degree of lightness constancy within a given field of illumination depends on the size of the field: the greater the size of a region of illumination, the greater the constancy within it. On the basis of these results, Katz formulated two laws of field size, according to which constancy grows as both the perceived size and the visual angle of each illumination field becomes larger. However, Bonato & Gilchrist (1999) studied perceived luminosity and reported that perceived size, not the visual angle, is the key variable in determining both lightness and luminosity threshold. However, in this project perceived size was not manipulated and contrast still increased by reducing the viewing distance. To interpret this outcome, it could be suggested either that effects of field size occur for visual angle as well as perceived size, or that when the display is closer to the observer, it appears somewhat larger due to some failure of size constancy.

3.2 Horizontal separation of the backgrounds in the *articulated-SLC*

The horizontal separation of the backgrounds in the *articulated-SLC* display in a VR cave reduces the perceived difference between the grey patches, and this reduction is proportional to the distance between them. This effect is in line with the high-level interpretation of the *SLC* phenomenon. This interpretative schema proposes that the SLC phenomenon occurs because the edge between the two backgrounds may be perceived, partially, as an illumination edge, rather than a pure reflectance edge (Gilchrist, 1988; Schirillo, 1999a, b; Soranzo, Galmonte & Agostini, 2009a; 2009b). Because of this, as the two grey patches share the same luminance but are perceived as being under different illuminations, they appear different in lightness. Furthermore, when both of the backgrounds are articulated, there are many different luminance pairs with the same polarity and the visual system might use this information to extrapolate the illumination intensity; this extrapolation is reinforced when the perceptual belongingness between these luminance pairs is increased (Soranzo & Agostini 2006a; 2006b).

In this regard, Soranzo & Agostini (2006a) suggested that strengthening the belongingness between two illumination fields may help the visual system to *aggregate* the surfaces, which are perceived as being differently illuminated, in the lightness dimension and *segregate* them in the apparent illumination dimension.

The horizontal separation of the backgrounds should reduce the strength of belongingness between the luminance pairs with the same polarity and this might reduce the perception that there are two different illumination fields. As a consequence, the contrast magnitude should reduce and this reduction should be proportional to the strength of belongingness between the luminance pairs with the same polarity.

Another way to interpret this is to consider Bergström's model (1977; 1994), which is based on three main assumptions:

1) The Commonality assumption: the visual system can discriminate changes in reflectance from those in illumination;

2) The Automaticity: the proximal stimulus is automatically analysed. If certain rules are followed, then it is not possible to ignore them. ("[...] the common component is not a matter of choice; it is dictated by the stimulus pattern" Gilchrist 2006, p. 203.).

3) Minimum principle: minimum but geometrically sufficient number of perceived sources of light is assumed (Bergström, 1994).

As mentioned above, Bergström (1977) asserted that the contrast effect increases by increasing the size of the backgrounds because the larger the surrounding field, the smaller the difference would be between the common component and the luminance level of the surround. Similarly, it can be said that the proximal invariance represented by the luminance pairs with the same polarity "automatically" induces the perception of two illuminations; the contrast effect increases by increasing the proximity between these luminance pairs. Paraphrasing Bergström, it can be said that increasing the proximity of luminance pairs with the same polarity reduces the difference between the common component and the luminance level of the surround.

3.3 Horizontal separation of the backgrounds in the *plain-SLC*

The horizontal separation of the backgrounds in the *plain-SLC* display presented in a VR cave increases the contrast magnitude. This effect is in line with the mid-level interpretation of the SLC phenomenon (see introduction). According to this approach, the visual system operates a two-dimensional partitioning of the luminance in global and local frameworks. The lightness of each surface derives from a co-determination process between the luminance ratio that each surface has with both the highest luminance in the local framework and the highest luminance in the global framework. The more one local framework is insulated from the rest of the visual scene, the more the lightness of its surfaces depend on their local value. Hence, separating the backgrounds should make the lightness of the patches in the SLC display more dependent to their local value, leading to an increase of the SLC phenomenon. This seems to be what actually happened in the *plain-SLC* condition.

1. Conclusion

The results that emerged from this experiment highlight the pros and cons of both the mid- and high-level interpretation of the SLC. The parallax manipulation allowed examination of both interpretations together and they both succeed in explaining that reducing the viewing distance increases the contrast effect. High-level theories explain this effect in terms of illumination perception, whilst mid-level theories focus on the local framework becoming stronger.

However, high-level theories provide a better explanation for the effects of background separation in the *articulated* condition, while mid-level theories better explain the background separation in the *plain* condition. The reason for this gap seems to derive from the fact that the mid-level theory does not include perceived illumination, while the high-level approach does not include an anchoring mechanism. It seems logical then, that a combination of the two approaches would lead to a more comprehensive lightness theory. Interestingly, this was also suggested by Anchoring Theory's initiators, who stated that: "[…] the next step would be to apply something like the highest luminance rule solely to the reflectance intrinsic image" (Gilchrist et al. 1999; p. 799). However there is still room for debate on how best to integrate these models. For example, Annan et al. (1996) reported that it is the highest luminance in a scene that appears white, and represents the anchor, not the highest reflectance. One way of combining the two approaches, which potentially overcomes this difficulty, might be to consider the highest luminance together with the number of luminance pairs with the same polarity as two factors that conjointly influence the contrast phenomenon.

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