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The Problem of Being *White*: Testing the Highest Luminance Rule

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It is a common understanding that white serves as an “anchor” for the visual system for lightness scaling purposes. By *lightness* we are referring to surface color perception in the achromatic domain. The importance of “surface white” is stated also in the literature about luminosity perception, where it is often claimed that in order for a region of the visual field to appear as self-luminous, its luminance must be somewhat higher than the luminance of a surface perceived as white under the same conditions of illumination. Implicit in this assumption is that the visual system is able to determine what is to be seen as white instead of luminous, glowing or light gray. A “highest luminance rule”, eventually corrected by an area factor, seems so far to be the best candidate. This approach has been applied to several lines of data with apparent success. However, below we will describe two experiments, one concerning lightness and the other perceived luminosity, that show the severe limitations of the highest luminance rule hypothesis.

1. Introduction

Lightness is the perceived shade of gray of a surface; it follows that the *lightness scale* is the array of grays, ranging from white to black, which can characterize the appearance of any achromatic surface. Vision scientists often refer to lightness as *perceived reflectance*. Such a terminology is justified by the fact that lightness appears to be the perceptual correlate of reflectance. In fact, in normal viewing conditions, it is expected that a sheet of paper that reflects 70% of the light should look light gray rather than middle gray or white. Nevertheless, just as in the chromatic domain, also lightness has to face constancy issues; that is, a surface should retain more or less the same lightness when modifications occur in the field of stimulation. Two types of modification in particular appear critical: changes in the level of illumination and changes in the luminance value of surfaces adjacent to the target region. The first type of variations affects the luminances of many surfaces, including that of an achromatic surface target. The second modification, instead, leaves the luminance of an achromatic surface target unchanged while the intensities of its surroundings change. These two types of variations affect sometimes dramatically, the lightness of a surface. With reference to illumination changes, Gelb’s effect[1)] shows that a low reflectance target, that should appear black, instead appears white when it is specially illuminated by a singular light source. If a smaller surface with greater reflectance is superimposed on the black surface, suddenly its lightness changes to a much darker shade of gray. In the case of changes to adjacent surfaces, the Simultaneous Lightness Contrast (SLC) display is a striking example. In this display, two gray surfaces, photometrically identical, are viewed against two different backgrounds—one white and one black, for instance. Observers report that the gray surface surrounded by white appears darker than the gray surface surrounded by black.

The aforementioned effects, and many others, call out for an explanation on how the visual system determines the lightness of a surface. It would seem that the system could simply solve the equation: $R=L/I$, where R stands for reflectance, L for luminance, and I for the illumination on a surface at a given time. But in fact this equation cannot be solved for not only is R unknown but also I.

Vision scientists have come up with several hypotheses to explain lightness, but we will focus our attention on three basic ideas. The first idea is that lightness is determined by the interactions of cells at the level of the retina (Hering2)); Jameson & Hurvich3)); Cornsweet4))). This process, known as lateral inhibition, well suits basic lightness illusions, such as Gelb's effect and SLC. In fact, both effects seem to depend on the luminance contrast ratios among neighboring areas. For instance, in SLC configurations the cells interested by the projection of the gray target on the white background will fire at a lower rate because of an inhibitory process activated by adjacent cells which respond to the white background. On the other hand, the cells responding to the gray target on the black background will receive less or no inhibition. Such differences in the encoding of identical luminances but with different surrounds will result in a lightness difference. Nevertheless, lateral inhibition based hypothesis cannot be easily applied to other well known illusions that are to be considered as modifications of the aforementioned effects, such as the Staircase Gelb illusion (SGI; Cataliotti & Gilchrist5)); Gilchrist et al.6))) and White's illusion7)).

The second idea concerns the importance of luminance ratios among neighboring surfaces in the scene (Wallach8, 9)); Land & McCann10))). The idea of a ratio based mechanism for lightness computation well suits lightness constancy as a phenomenon, but fails to address many of the numerous lightness constancy failure illusions, such as the abovementioned SGI and White's illusion.

Slowly but surely a third hypothesis is being seriously considered in the vision community. This hypothesis is based on the realization of the lightness scaling problem (Wallack8,11)); Lie12)); Li & Gilchrist13))) and the need for an *anchoring principle* in order to solve this problem. Briefly, the problem consists in the fact that the only input information available to the visual system is given by the map of luminances as projected on the retina. It is obvious that neural encoding of absolute luminance values would result in a total lack of lightness constancy. In fact, if lightness depended on absolute luminance encoding, an achromatic surface would have the chameleonic property of changing its appearance as the illumination changes in intensity. Therefore the necessary idea that the system works with luminance ratios (Gilchrist14))). And it is here that the scaling problem becomes manifest, because a specific luminance ratio between adjacent surfaces could indicate any in an infinite pair of lightness values. Hence the necessity for the system to employ the use of an anchor—a surface luminance that will serve as a reference for all other surface luminances, allowing for reliable lightness scaling. There have been several proposals for what this anchor should be. Some have talked about a double anchoring principle (the darkest surface would be assigned the value black, the brightest the value white), and others have advanced the hypothesis that the system uses the mean luminance of the visual scene as an anchor. The current idea is that the highest luminance in the scene constitutes the anchor for lightness scaling (Wallach[9]; Land & McCann[10]). The validity of the hypothesis was confirmed experimentally by Gilchrist and his collaborators (Bonato & Gilchrist[15]; Cataliotti & Gilchrist[5]; Li & Gilchrist[13]; Gilchrist et al.[6]). More formally stated, the highest luminance within a given framework for lightness computation will be tagged as white and serve as the anchor for the lightness assignments of other surfaces within the framework.

It appeared obvious right away that the highest luminance rule had a problem: the existence of self-luminous surfaces. These are objects that appear to glow or even to emit light. Usually such surfaces have luminances that are far more intense than any surface perceived as white. The logical problem determined by these surfaces for the highest luminance rule is partially overridden by introducing an area factor according to which only surfaces that reach a certain size can be used as an anchor (white) for lightness scaling purposes.

Yet, the problem of self-luminous surfaces still remained open. Bonato & Gilchrist[15,16] ran several experiments aimed at defining the luminosity threshold, that is the luminance at which an achromatic surface would change its appearance from opaque with a certain lightness to glowing or self-luminous with a certain brightness. What they found is that the luminance threshold is directly correlated to the lightness anchor. That is, a surface will appear self-luminous or glowing when its luminance is approximately 1.7 times that of another surface that would appear white viewed under the same conditions of illumination. In other words, it is suggested that white serves as an anchor for both lightness and luminosity perception.

Despite the huge quantity of data supporting the highest luminance rule and the consequent role of white, we find that very little research has been done to understand 'white' as a percept. In the following paragraphs we will illustrate and discuss data from experiments showing that: i) within the SGI, luminance adjacency can co-determine which surface is to be seen as white; and ii) that white is not the anchor for luminosity perception, and when asked to adjust a surface to perceived white, the variability within and between subjects is incredibly high, suggesting that white as a percept is more complete than what usually assumed.

2. What is white in the Staircase Gelb illusion?

When five adjacent squares with reflectances ranging from low to high—in Munsell values, such squares would be 2.0, 4.0, 6.0, 8.0, 9.5—are illuminated by an additional light source, so that the special illumination interests only the five squares, then what one sees is a compressed range of grays, namely from Munsell 6.0 (middle gray) to 9.5. What produces such compression?

Models based on lateral inhibition or receptive fields do not predict lightness compression for such an illusion. A new theory, known as the Anchoring theory (Gilchrist et al.[6]), appears to be able to account for this and many other lightness effects.

2.1 The anchoring theory applied to SGI

The way the visual system computes lightness according to the Anchoring theory can be summarized in four basic steps:

1) The visual scene is segmented into hierarchical frameworks. A surface, that from now on we will call target, belongs to at least 2 frameworks: a *local framework* and a *global framework*.

2) The visual system analyses each framework to determine which surface will serve as an anchor. It will take into account basically two factors, the luminance of a surface and its dimensions relative to other surfaces in the same framework. Though the area factor is yet to be quantified in relative terms, it is suggested that a surface with the highest luminance and an average size comparable to those of the other surfaces within the framework will serve as anchor and will be assigned the value *white*.
3) The target will be compared to the anchor (white) within each framework to which it belongs. Preliminary lightness assignments—that is values related to a specific anchor and framework—are then applied to the target.
4) The perceived lightness of the target will be determined by a weighted average of all its preliminary lightness assignments from each framework.

In the SGI, the group of adjacent five squares constitutes the local framework, and within that framework the white square (Munsell 9.5) becomes the anchor while all other squares are scaled accordingly. Given that the group of five squares displays a 30 : 1 luminance range (a black surface usually reflects 3% of the light illuminating it, while a white surface reflects in average 90%), no compression should occur at this stage; hence the five squares should be labeled as black, dark gray, middle gray, light gray, and white.

In the SGI, the group of five squares also belongs to the entire visual scene, that is to the laboratory in which they are seen. This constitutes the global framework. Due to their relatively small size with respect to other surfaces present in the global framework (walls, tables, other random surfaces), none of the 5 squares can become the anchor. The anchor must be found in some other surface with a luminance-area ratio such to satisfy both the highest luminance rule and the area rule. Nevertheless, because of the special illumination conditions, each square in the adjacent group of five have luminance that is equal or higher than the actual anchor determined in the global framework. Hence, each square is labeled as white in the global framework.

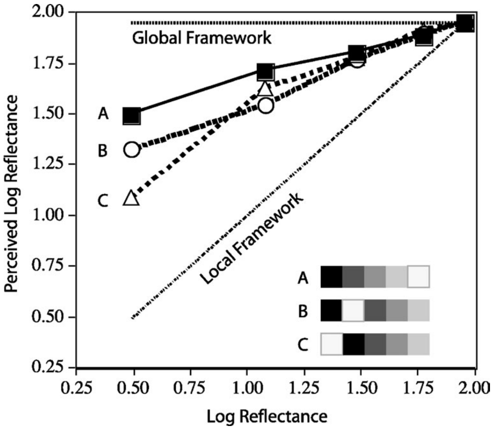

Fig. 1. The Staircase Gelb illusion and lightness compression. Curve A shows the data for the standard SGI display (the five squares are organized in scale from the darkest to the brightest). Curves B and C show data from two experiments, with modified SGI displays, where the white square is placed next to the black square. The two straight lines are theoretical curves for lightness assignments within the Local and Global frameworks, as specified by the Anchoring theory.

The perceived lightness of the five squares comes from a weighted average of the local and global frameworks (Fig. 1, curve A). As one can readily see, the illusion depends on the lightness assignments within the global framework. The local framework, instead, displays a strong degree of constancy.

2.1.1. Empirical findings that challenge the Anchoring theory

The Anchoring theory predicts no differences in lightness due to local interactions between neighboring surfaces. Nevertheless, it was recently observed that the position of the highest luminance (Munsell 9.5) within the five squares can strongly influence the compression factor otherwise observed when the five squares are displayed in scale, from darkest to brightest (Annan & Zavagno, in preparation; Bressan & Zavagno, in preparation). In fact, when the white square is positioned next to the black square, the last is matched with a much darker gray on an extended Munsell chart (a chart where 35 levels of gray are displayed for the observer to pick a match from). Curves B and C in Fig. 1 show the drop of compression obtained in such cases. It appears obvious from the rational of the Anchoring theory itself that the difference in compression can be caused only by the effect of luminance adjacencies within the local framework.

If a bright surface can influence the appearance of a dark surface in the SGI, can a dark surface in turn influence a bright surface in the same type of configuration? In terms of low level mechanisms, a dark surface will exert less inhibition than a bright surface, and such a difference can be conceptualized in terms of mutual interactions between adjacent surfaces. But in terms of the *highest luminance rule*, nothing should affect the appearance of the surface that, having the highest luminance and the adequate area ratio within the local framework, should be the anchor. In fact, if the anchor were affected by adjacent lower luminances, how would the system solve the scaling problem?

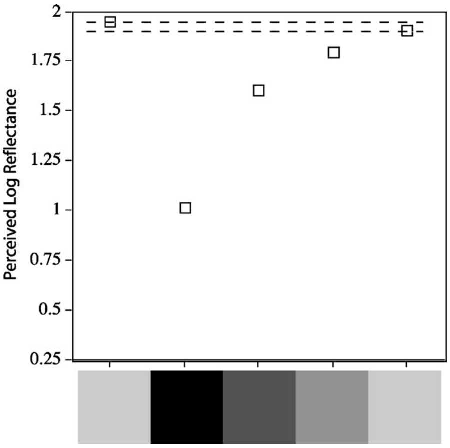

Fig. 2. Data from an experiment with a modified SGI where two light-grays (LG1 and LG2, both Munsell 8.0) are the highest lumnances in the local framework. The Anchoring thory predicts no differences in appearance btween LG1 and LG2, despite their local contrast differs. However observers matched LG1 (next to the lowest luminance within the group, see Table 1) with white, and LG2 (next to an intermediate luminance) with a light gray. The difference in appearance is about half a Munsell step, magnitude which approximates the difference observed between two photometrically identical gray targets in the Simultaneous Lightness Contrast illusion.

2.2 Two equal highest luminances that appear different

If luminance adjacencies also affected the highest luminance, then the data in Fig. 1 would look different. In fact, it appears impossible to test the highest luminance rule, given that by definition the highest luminance will always be assigned the value *white* in the local framework. However, we noticed from reports by our observers that there seems to be a ceiling effect. In fact, over 80% of the observers declared they could not find a real match for the brightest square. Their explanation was, invariably, that the brightest square was too bright, and it appeared to glow or self-luminous.

Table 1. Luminances for the modified SGI display (lightness experiment).

Percept in normal viewing conditions	Munsell	Luminance (cd/m^2)
Light gray 1 (LG1)	8.0	3040
Black (B)	2.0	183
Dark gray (DG)	4.0	830
Middle gray (MG)	6.0	1800
Light gray 2 (LG2)	8.0	3280

Such a finding lead us to build a new display where we lowered the highest luminance by replacing the Munsell 9.5 square with a second Munsell 8.0 square (Fig. 2). This solution allowed us to bypass the ceiling effect and test directly the highest luminance rule. If the highest luminance rule held, the two 8.0 squares should both become anchors in the local framework and should hence both be matched with white (9.5) on the Munsell chart.

Twelve subjects performed matches for the modified SGI with two equal highest luminances. Table 1 shows the Munsell value of each square and the actual luminances used during the experiment. Notice that the luminances of the two Munsell 8.0 squares are slightly different, with the luminance of the light gray square (LG2) next to the middle gray one (MG) being over 200 cd/m^2 more intense than the light gray square (LG1) next to the black one (B). The results are shown in Fig. 2, and as one can readily see, LG1 is matched as white while LG2 is matched as an off white or a light shade of gray, despite the fact that the last has actually a greater luminance. A paired t-test confirms the statistical difference between the two target ($t=6.139$; $p<0.0001$).

Our findings suggest that the highest luminance rule alone cannot predict which surface will be seen as white. In fact, it fails to predict that the highest luminance will be seen as white. The second important consideration is that local luminance interactions seem to be effective in SGI displays, and that given proper luminance conditions, the interactions between bright surfaces and dark surfaces are mutual, though a comparison between experiments suggests that there are differences in magnitude, with the biggest effects observed on surfaces with lower luminances (Annan & Zavagno, in preparation).

3.0 What is white and what is luminous?

Luminosity is the visual experience concerning surfaces or regions in the visual field that appear to glow or to emit light. Luminous is the sun in a limpid sky, or the moon at night, the flame of a candle and the stars; luminous is also a switched on light bulb or the windows of a distant building in the dark, when the corresponding rooms are illuminated.

For a vision scientist, the experience of luminosity should be a fascinating question to investigate, for one actually sees the intangible matter that shapes our visual world and that instead is itself most often invisible, lost in the shapes that it makes visible. However, there have been few studies expressively dedicated to luminosity as a percept, and the understanding of how the experience of luminosity originates in the visual system is still a matter of debate.

As anticipated in the introduction, some of the most recent experimental studies dedicated to the experience of luminosity focused their attention on the definition of a threshold value, at which point an achromatic surface would change in appearance from opaque to luminous. Clear attempts of a phenomenological description of the experience of luminosity can be found in Katz(17), who thought of the luminosity threshold in terms of a “definite absolute light-intensity" (p. 27). The idea of an intensity threshold is somewhat embedded in every scientist who dealt with problems concerning color perception. Evans[18] for example stated that "Grayness and fluorence are mutually exclusive perceptions from a single stimulus" (p. 98). In other words, what appears luminous cannot appear gray and vice versa (Wittgenstein[19]), which also means that what appears luminous in the achromatic domain must be at least white. Such concepts necessarily lead to the idea of a threshold for luminosity somewhat dependent to what can be seen as white within a specific visual scene. The idea actually received its first formulation by Hering [2], as reported by Katz [17]. Hering suggested that a surface would appear self-luminous only when its luminance is somewhat greater than white.

The hypothesis expressed by Hering found experimental confirmation in the research by Bonato & Gilchrist [15,16], who discovered that a surface appears self-luminous when its luminance is about 1.7 times that of another surface which, if present in the same visual scene, would appear white. This finding puts the luminosity threshold at the utmost level of the lightness scale, passed which level surfaces change from an opaque mode of appearance to a film color mode of appearance. Such a luminosity threshold also means that white intended as surface color (lightness) is the standard comparison, or the *anchor* in terms of the Anchoring theory, also for the perception of luminosity. In fact, if L_T stands for the luminance of the target and L_W for the luminance of a surface perceived as white, we have that L_T = luminosity if and only if $L_T \geq 1.7 \cdot L_W$.

Linking the luminosity threshold to white introduces some logical consequences concerning the effects of backgrounds and illumination. In fact, according to the Anchoring theory, the definition of the anchor happens within specific frameworks, a fact which greatly reduces both the effect of background luminances and of illumination. Such features would influence the definition of the anchor, and therefore of the luminosity threshold, only to the point that they are somewhat embedded in a local framework, and therefore become codeterminants of the luminance anchor. These consequences have found empirical ground in many experiments by Bonato & Gilchrist [15,16].

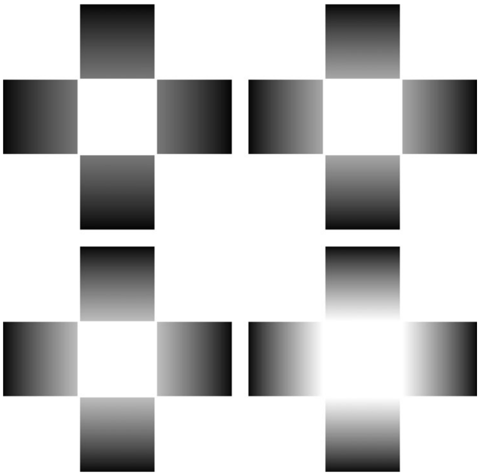

Fig. 3. The Glare effect. As the luminance gradients increase in range, the central target appears brighter, despite the target itself is photometrically constant.

3.1 The Glare effect: a case where the luminosity threshold does not apply

The Glare effect (Zavagno[20]), however, represents a challenge for the luminosity threshold hypothesis, for in its standard shape the illusion shows a white square that appears self-luminous when it is embedded in a cross made of smooth luminance gradients. As one can see from Fig. 3, there is no doubt on the fact that the there is a functional relationship between the luminance of the central square and the luminance range of the surrounding gradients. Recent experiments show that such a functional relationship is also extended to the luminance of the background (Zavagno & Caputo[21)]).

The existence of the Glare effect alone shows the severe limitations of both the highest luminance rule and of the luminosity threshold hypothesis. However, one still needs to ask what is seen as white when one experiences the Glare effect.

3.1.1 The luminosity threshold versus luminance gradients

According to the formula $L_T \geq 1.7 . L_W$, a surface present in the same global framework with the glare effect should appear white at luminances somewhat below that necessary for perceiving the target surrounded by luminance gradients as self-luminous. To test such a hypothesis an experiment was designed, the settings of which are described in Fig. 4 and Table 2 (Zavagno & Caputo, accepted pending revision). Observers' task was to adjust the luminance of one target to self-luminosity (Tg) and that of the other target to perceived white (Tw) on a CRT. The cross containing Tg would change in luminance range, with Tg and the edges adjacent to Tg equal in luminance. The cross containing Tw remained black throughout all trials. Two room illumination conditions were used (normal illumination, dark room) and three screen backgrounds (dark gray, middle gray, light gray).

Figure 4 and Table 1 display the mean adjustments as performed by six observers. The first thing to notice is that luminances for Tw are consistently greater than luminances for Tg, meaning that the Glare effect is capable of showing luminosity at luminance levels far below those necessary to perceive surface white within identical conditions of illumination. This fact also confirms the possibility to perceive self-luminous grays, a percept first described by Wallach[8,11)] who falsified beforehand both Evans and Wittgenstein. Finally, the parallelism between curves of the same illumination suggests that background and illumination appear to affect in equal measure both perceived

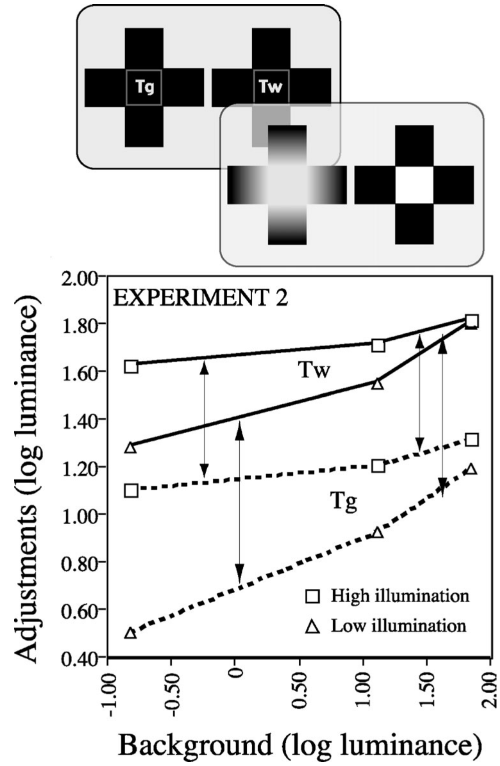

Fig. 4. Data from an experiment where observers were asked to adjust Tw to white and Tg to luminosity. Three backgrounds (see Table 2) and two room illumination conditions were employed (bright room, dark room). The experiment was divided into two session; the first session consisted in adjustments performed in a bright room. Observers were randomly asked to adjust first either Tw or Tg. First adjustment was not statistically significant. The main finding is that adjustments for white (Tw) require higher luminances than adjustments for luminosity (Tg). This suggests that for luminosity perception luminance gradients surrounding the target are more relevant than the luminance of the target itself.

Table 2. Mean adjustments and Standard Errors for Tw and Tg (luminosity experiment).

Background (cd/m^2)	Normal room illumination				Dark room			
	White (Tw)		Luminosity (Tg)		White (Tw)		Luminosity (Tg)	
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
0.15	41.36	6.92	13	1.4	19.04	4	3.3	1.2
13	51.25	8.7	16.56	6	34.73	5.5	8.67	3.8
70.3	65.18	6.1	21.26	5.8	62.56	6.7	16.05	5

surface white and the luminosity threshold in the Glare effect.

Comparing the results in Table 2, one also sees that standard errors for the two type of adjustments are similar; nevertheless, those for luminosity adjustments (Tg) are slightly inferior than those for White adjustments Tw. This suggests that if there is a cognitive problem in defining or recognizing what is luminous (Bonato & Cataliotti[22]), the same problem haunts also what is to be seen as white.

3.2 A new hypothesis for the luminosity threshold

Our experiment leads to two conclusions. The first is that luminance gradients appear to have a crucial role in generating vivid impressions of luminosity. Such fact has gone unnoticed because recent and passed experiments expressively attempted to *clear* the experimental settings from features considered as *visual noise*: gradients, flare, blurriness, etc. (Ullman[23]; Bonato & Gilchrist[15]). The second conclusion is that white is not the anchor for luminosity perception.

If white is not the anchor for luminosity perception, then what does the 1.7 ratio to white stand for? In our opinion such a ratio defines the level of luminance intensity at which physical effects of light scattering and of light diffraction occur at the proximal level of stimulation (Simpson[24]; Bettelheim & Paunovic[25]; Beckman, Nilsson, & Paulsson[26]). Such effects, as parts of the retinal image, must be held to play a crucial role as far as luminosity perception is concerned. In our experiment, subjects determined artificially similar features on the distal stimulus, thus achieving luminosity at luminance levels far below those normally requested outside a laboratory. This hypothesis also suggests that lightness and luminosity depend on separate mechanisms, even though communication between mechanisms is not denied in principle.

4.0 Conclusions

At a first glance, the highest luminance rule appears as a good candidate to define what is to be seen as white. Both the Anchoring theory (Gilchrist et al.[6]) and the Double Anchoring theory (Bressan, accepted pending revision) agree in using white as an anchor in several stages of lightness processing. Both theories also seems to require white as a comparison for luminosity perception as well.

However, we described two separate experiments, which are just examples from a wider sample of experiments, that show: i) the intrinsic limitations of the highest luminance rule, ii) that *white* intended as surface color is far from being a well defined percept, and iii) that white is not directly involved in determining what is to be seen as luminous. Such conclusions throw some shadows on the concept of white as having a special status for the visual system, as far as lightness or luminosity mechanisms are concerned.

We think that the idea of white as having a special status for the visual system is in part a consequence of another fact, that is that white seems to have a special status at higher cognitive levels. For example, we often hear that a white wall helps to show the "true colors" of paintings. And indeed it is true that a blue or a red observed against a white background will look particularly bright. But on the other hand, a light gray or a yellow will not appear that striking on the same white wall. However, such colors will become strikingly "alive" as soon as the background is changed to black. In other words, luminance contrast between surfaces seems to be the real issue rather than the luminance of the background alone.

Another example comes from the fact that white is in many senses also an industrial standard. For example, a *white* surface should have certain physical properties, such as that of reflecting uniformly along the entire visible spectrum about 90% of the luminous energy illuminating it. Nevertheless, one cannot deny that there are many different types of white when we just consider *white* paper. Which one is the real or the best white?

Finally, one might also want to consider white balance algorithms in digital cameras, which take into account the color temperature of the illuminant to avoid, for example, yellowish images with indoor artificial lighting. However, similar algorythms, along with other industrial standards, have to rely ultimately on what the human eye perceives as white, which, as the Gelb effect teaches us, can be a tricky matter.

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