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Classical and inverted White's effects

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Abstract. In classical White's effect, intermediate-luminance targets appear lighter when they interrupt the dark stripes of a grating and darker when they interrupt the light stripes. The effect is reversed when targets are of double-increment or double-decrement luminance, relative to the luminances of grating stripes. To find a common explanation for classical and inverted effects, we ran two experiments. In experiment 1, we utilised intermediate-target displays to show that perceived transparency dominates over occlusion only when the target luminance is close to the luminances of top regions. This result weakens transparency-based accounts of White's effect. In experiment 2, we varied grating contrast and target luminance to measure the classical effect in seven intermediate-target cases, as well as the inverted effect in four double-increment and four double-decrement cases. Both types of effect are explained by a common model, based on assimilation to the top region and contrast with the interrupted region, weighted by adjacency along the luminance continuum.

1 Introduction

White's effect is a striking lightness illusion in which targets that interrupt the dark stripes of a high-contrast grating appear lighter than targets that interrupt the light stripes (White 1979).

Figure 1 shows the classical display with elongated intermediate-luminance targets. Each T-junction type is described by a trigram, reflecting the luminance order of the three regions, from the darkest (left letter) to the lightest (right letter). For instance, IWT displays are those in which interrupted stripes are the lowest, targets are intermediate, and top stripes are the highest in luminance.

(a) IWT (b) TWI

Figure 1. Classical White's effect with a target luminance lying within the luminances of grating stripes. Targets that interrupt dark stripes (a) appear lighter than targets that interrupt light stripes (b). T-junctions are labelled according to the luminance order of the three regions (IWT on the left and TWI on the right). Both IWT and TWI junctions preserve contrast polarity along the top edge.

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The direction of the effect is incompatible with a simple border-contrast model. Grey rectangles surrounded by more white than black appear *lighter* than grey rectangles surrounded by more black than white.

The amount of the effect is not easily explained either. The lightness difference between the two targets can be three times larger than the corresponding simultaneous lightness contrast (SLC) with grey-on-white and grey-on-black targets (White 1981).

Recently, it has been reported that the direction of White's effect is reversed when both targets are increments or decrements, relative to grating luminances (Gerbino and Ripamonti 1997; Ripamonti and Gerbino 1997; Spehar et al 1997, their figure 2). In double-increment (figure 2) and double-decrement (figure 3) displays, targets that interrupt dark stripes appear darker than targets that interrupt light stripes.

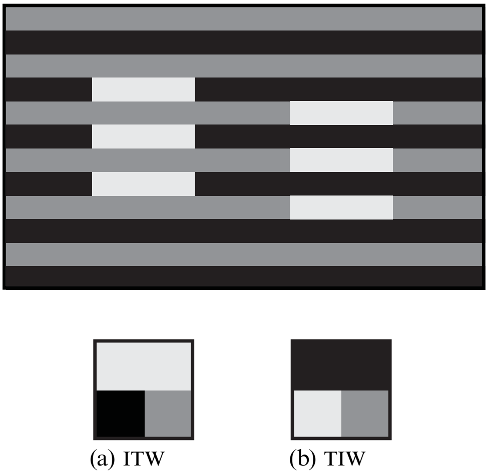


Figure 2. Inverted White's effect with double-increment targets. Targets that interrupt dark stripes (a) appear darker than targets that interrupt light stripes (b). Only TIW junctions preserve contrast polarity.

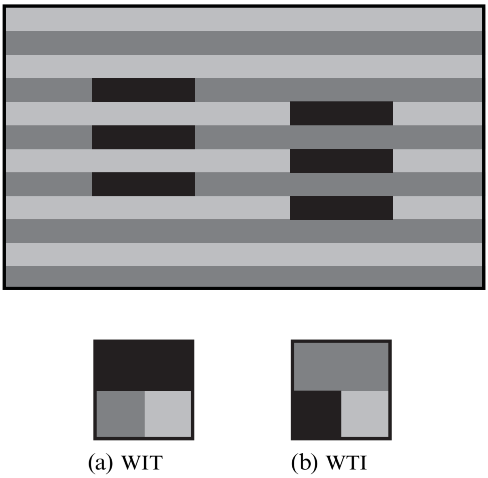


Figure 3. Inverted White's effect with double-decrement targets. Targets that interrupt dark stripes (a) appear darker than targets that interrupt light stripes (b). Only WIT junctions preserve contrast polarity.

So far, little experimental work has been explicitly devoted to lightness effects in double-increment and double-decrement White's displays. Spehar et al (1995b, their figure 5) found data partially consistent with the inversion of White's effect in double-increment cases, but their conclusions emphasised only the most prominent aspect of such data: the collapse of the classical effect outside the range defined by intermediate-luminance targets. Spehar and Zaidi (1997) described complex interactions between increment and decrement targets embedded in second-order luminance-contrast White's displays. Anderson (1997, his figure 10) used double-increment and double-decrement White's displays to demonstrate the failure of assimilation in predicting the sign of the lightness illusion.

Here, we confirm that lightness deviations also occur with double-increment and double-decrement versions of White's display, and address a basic question: are classical and inverted White's effects compatible with a single explanation, or do they require separate explanations, each tailored to different luminance combinations?

Following the approach taken by Spehar et al (1995b), we looked for regularities in the direction and amount of lightness effects as a function of luminance combinations.

We suggest that a common explanation for the classical effect with intermediate targets and for the inverted effect with nonintermediate targets can be based on the luminance ordering of the three regions meeting at T-junctions of White's display: the target (luminance W), the interrupted stripe (luminance I), and the top stripe (luminance T).(1)

Our explanation utilises geometric and photometric information available at T-junctions in a consistent manner, without invoking surface stratification and three-dimensional (3-D) organisation as necessary constraints for the occurrence of classical and inverted White's effects. Such information is captured by the labelling of T-junctions introduced in figures 1 to 3.

1.1 *Concepts and mechanisms*

Several explanations of White's effect have been offered so far. Here we discuss them in the context of relevant theories of lightness perception.

1.1.1 *Assimilation.* The assimilation hypothesis predicts that the lightnesses of both sets of targets (interrupting dark or light stripes) are shifted towards top stripes; therefore, they are shifted in opposite directions. White (1981) considered two types of assimilation. The first type is contrast reduction due to pattern-specific inhibition and is maximal when target and grating orientations are the same. This hypothesis considers the region resulting from the grouping of targets and neighbouring portions of top stripes as a unit, segregated from the surrounding grating. However, White (1981) manipulated orientation and found that contrast reduction was consistent with pattern-specific inhibition in the grey – white region but not in the grey – black region. No explanation was offered for such a difference (White 1981, page 229).

The second type of assimilation is the effect described by von Bezold (1862/1876). In gratings, von Bezold's assimilation can be modelled by a spatial-averaging process in which the target colour deviates towards the alternating colour, before complete fusion (ie loss of grating detectability). Its strength increases as spatial frequency increases (Helson 1963; Wandell 1993). Von Bezold's assimilation can be used as a general concept, possibly corresponding to the output of different mechanisms (Whittle 1994, pages 136 – 141).

Any explanation based on assimilation alone accounts for the direction of the classical effect in intermediate-luminance-target displays, in which the targets neighbouring the light top regions appear lighter than those neighbouring the dark top regions. But it fails in double-increment and double-decrement cases, in which the targets neighbouring the light top regions appear darker than those neighbouring the dark top regions.

1.1.2 *Local contrast.* According to the local-contrast hypothesis, lightness depends on luminances along the border. Targets surrounded by more black than white should appear lighter than targets surrounded by more white than black. In White's display

(1) A top stripe is so labelled with reference to an upright T, independently of its actual position in the display, where it can be a top stripe or a bottom stripe, relative to different targets.

with elongated targets that share their shorter sides with the interrupted stripes the effect is consistent with local contrast in double-increment and double-decrement cases, whereas it is inconsistent in intermediate-target cases. According to local contrast, the amount of White's effect should depend on the aspect ratio of target bars. However, this is not the case, as mentioned by White (1981) and confirmed by Moulden and Kingdom (1989), who used square targets.

1.1.3 *Low-level filtering.* Blakeslee and McCourt (1999, 2000) proposed an oriented difference-of-Gaussians (ODOG) model that explains several brightness/lightness illusions, including White's effect with intermediate targets. The performance of the ODOG model in double-increment and double-decrement cases has not been evaluated yet, but there are reports indicating that an inverted effect might occur (Spehar, personal communication).

1.1.4 *T-junctions.* More complex interactions are taken into account in the local-corner model tested by Moulden and Kingdom (1989, 1990). They credited Morgan and Ward for a specific prediction about T-junctions: on the basis of the output of peripheral receptive fields, contrast between regions sharing the T-stem should be larger than contrast between regions sharing the top edge of the T. The local-corner model is compatible with other models that relate lightness to T-junctions.

The critical role of T-junctions in mid-level vision and lightness perception has been stressed by several authors (Anderson and Julesz 1995; Anderson 1997; Bressan 1997; Todorović 1997) and is an important aspect of the selective integration model (Pessoa and Ross 1997; Ross and Pessoa 2000).

Typically, T-junctions are considered as local cues indicating that regions that share the stem of the T are more unified than regions that share the top edge of the T. In White's display, target bars belong to interrupted stripes and are isolated from top stripes. Belongingness modulates lightness perception (Benary 1924/1939; Agostini and Proffitt 1993; Gilchrist et al 1999; Adelson 2000).

The anchoring theory (Economou et al 1999; Gilchrist et al 1999) provides a common explanation for SLC and White's effect. Intermediate-target SLC is attributed mostly to the lightening of the target surrounded by black. Such illusory lightening results from a compromise between local (target = white) and global (target = veridical grey) assignments, taking the reference to a white framework as the standard for veridicality. The target surrounded by white is perceived veridically, because local and global assignments are the same (target = veridical grey). A minor departure from veridicality is actually expected in the target surrounded by white because of the reduced luminance range (compared to the canonical black-to-white range).

In White's display, T-junctions modulate the belongingness of regions and consequently the relative strength of local/global assignments. The amount of White's effect would be maximal if regions divided by the top edge were totally isolated. In such a case, IWT targets should appear white and TWI targets should appear veridical grey, leading to a total amount of White's effect larger than SLC. If isolation along the top edge of the T-junction were partial, then the amount of White's effect would be reduced. However, in the anchoring theory the effect is attributed mostly to the non-veridical perception of targets that interrupt dark stripes.

In double-increment cases, the anchoring theory predicts no effect [Gilchrist et al (1999), page 815; but see Actis-Grosso and Bressan (2000)]. In double-decrement cases, the anchoring theory should predict an effect in the classical direction, because targets that interrupt light stripes are perceived veridically, whereas targets that interrupt dark stripes become lighter as a consequence of the shift of interrupted dark stripes towards white. This shift should depend on their relative isolation from top light stripes, which makes them the local anchor.

1.1.5 *Figural contrast.* The figural-contrast hypothesis is based on figure–ground organisation and parsing of T-junction segments into contours of overlapping surfaces. Top segments become the occluding contours of continuous stripes. Regions sharing the T-stems (ie targets and interrupted stripes) amodally continue behind top stripes. Targets are unified into a single figure and, because of inclusion, appear as a superposed figure on the continuous background surface resulting from the amodal completion of interrupted stripes (figure 4).

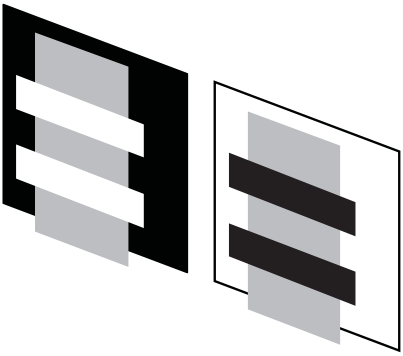


Figure 4. Stratification of surfaces in the left and right portions of classical White's displays according to the occlusion solution.

According to figural-contrast theories, effective borders depend on figure–ground organisation because the background is the frame of reference for the colour of the figure and not vice versa (Wolff 1934; Koffka 1935; Kanizsa 1979). In White's display, the grey rectangle perceived on a black background (behind white stripes) appears lighter than the grey rectangle perceived on a white background (behind black stripes).

In White's display, where 3-D stratification is a function of T-junctions, the figural-contrast hypothesis makes the same predictions as 2-D models based on the local analysis of T-junctions: it explains the classical White's effect but not the inverted effects obtained in double-increment and double-decrement cases.

However, notice that White's effect occurs also when targets are perceived as coplanar to (or just behind) T-top regions and clearly separated from the far background (Zaidi et al 1997).

Lightness deviations observed in White's effect are the contrastive byproduct of figure–ground organisation by the FACADE (form and colour and depth) network (Kelly and Grossberg 2000). FACADE has not been tested with double-increment and double-decrement target displays. However, Grossberg (1997; Kelly and Grossberg 2000, their figure 4) has discussed the conflict between depth ordering supported by geometric information available at T-junctions and photometric information conveyed by the luminance ordering at ITW junctions.

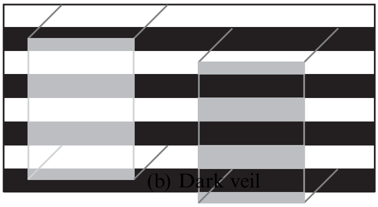
1.1.6 *Colour-illumination invariance.* Colour–illumination invariance (Koffka 1935) is a general notion consistent with the albedo hypothesis (Beck 1972), the taking-into-account approach (Rock 1983), component analysis (Bergström 1994), and inverse optics. The recovered surface colour is an inverse function of the illumination attributed to the surface. If we assume that the local illumination level depends on the background luminance, after surface segmentation based on occlusion cues like T-junctions, then a given luminance on a dark background will appear lighter than the same luminance on a light background.

Pictorial configurations like White's display might elicit a constancy mechanism based on such an invariance and produce an effect that is weaker than in ordinary vision (Gilchrist 1988) but in the same direction. Unfortunately, also this hypothesis does not account for the inverse effect in double-increment and double-decrement cases.

1.1.7 *Layer analysis.* More complex interpretations of White's effect follow from layer analysis, ie from the attempt to extend the scission metaphor beyond the recovery of surface reflectance and illumination to transparent layers and media. In pictorial displays perceived as superposed layers (Adelson 1993; Somers and Adelson 1997), lightness illusions are much larger than those obtained from comparable luminance patterns perceived as a mosaic of surfaces under a common illumination, like in classical SLC displays.

Consider the possibility that White's displays provide information also about shadows and transparent layers, because T-junction patterns that preserve contrast polarity can be considered to be degenerate cases of layer-compatible X-junctions (Sambin 1983; Watanabe and Cavanagh 1993; Anderson 1997). In displays with intermediate-luminance targets, both IWT and TWI junctions admit two interpretations: occlusion (figure 4), as implied by figural-contrast and colour-illumination-invariance hypotheses, and transparency (figure 5).

(a) Light veil



(b) Dark veil

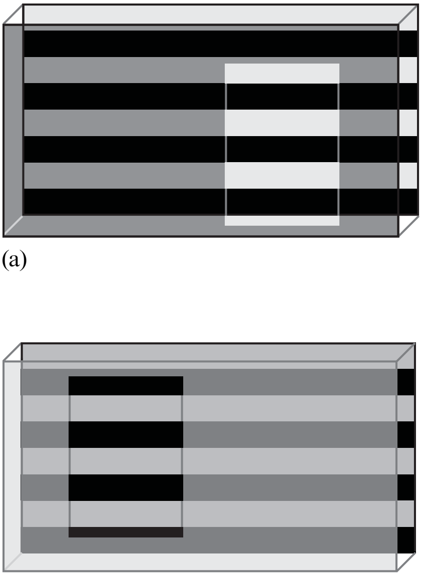
Figure 5. Stratification of transparent layers and opaque surfaces in the left and right portions of classical White's displays.

The transparency interpretation provides an alternative account of the classical White's effect, based on the shift of target lightnesses towards the perceived reflectances of recovered layers. As specified in section 2.1, the recovered reflectance of a layer resulting from the unification of targets and neighbouring portions of top stripes is equal to the reflectance of top stripes (given that a T-junction can be a degenerate X-junction only if the top luminance is not modified by the superposed layer). Therefore, if contrast polarity along the top edge of the T-junction is preserved, and a transparency interpretation is instantiated, each target lightness is shifted towards the luminance of the top stripe.

In double-increment and double-decrement White's displays, only one of the two T-junction types preserves contrast polarity and admits a transparency interpretation: TIW in double-increment displays (figure 2a) and WIT in double-decrement displays (figure 3b). ITW (for double increments) and WTI (for double decrements) junctions are compatible only with occlusion, because transparency is incompatible with the reversal of contrast polarity along the top edge of the T-junction. This constraint means that a trigram is transparency-compatible only if W and I are on the same side (either left or right) of T.

As shown in figure 6, the transparent layers consistent with double-increment and double-decrement targets surround the regions resulting from the unification of targets and neighbouring portions of top stripes, which share the higher contrast part of TIW and WIT top edges. Therefore, no obvious prediction can be derived from a transparency-based account of double-increment and double-decrement cases.

Anderson (1997) proposed a more general use of scission as a possible explanation of White's effect. He suggested that scission is instantiated by the simple occurrence of contrast-polarity-preserving top edges, independently of the specific 3-D perception. Scission might also occur when top stripes are perceived in front (as shown in our figure 4). In general, target luminances are split into two layers (Anderson 1997, his figure 8): one layer is assigned the same lightness as the stripes that, in the stimulus, are interrupted by the target; the other is assigned the residual lightness (depending on the decomposition



(a)

(b)

Figure 6. Stratification of transparent layers and opaque surfaces: (a) in the right portion of double-increment-target displays, and (b) in the left portion of the double-decrement-target displays.

function). Notice that a similar mechanism was utilised by Musatti (1953) to explain all contrast effects as byproducts of the tendency to maximise homogeneity.

Decompositions in opposite directions for the two targets account for the classical White's effect, amounting to the sum of two (approximately) equal lightness illusions.

1.2 *Overview of experiments*

In experiment 1, we focused on perceived transparency in intermediate-target displays, because we observed that not all displays with contrast-polarity preserving T-junctions (section 1.1.7) give rise to the actual perception of transparency. If perceived transparency occurs only in special cases, one must specify under which circumstances it can be considered as a valid explanation of White's effect.

In experiment 2 we measured the amount of classical and inverted White's effects as a function of ordinal and metrical relationships between the three relevant luminances.

To select luminance values on a scale that approximates the lightness continuum, we used the following power transformation: $L^* = L^{0.548}$ (with the asterisk indicating a power-transformed luminance). The value of the exponent was chosen for practical reasons related to monitor calibration, and allowed us to approximate Munsell values with equal perceptual steps on a 0 – 10 scale.

2 Experiment 1: Transparency versus occlusion

When the target luminance is intermediate between the grating luminances (figure 1), both occlusion and transparency interpretations are consistent with ecological optics. Occlusion is always a possible percept (figure 4). However, layer analysis—common to the episcotister model (Metelli 1970, 1974; Gerbino et al 1990; Gerbino 1994), scission (Musatti 1953; Anderson 1997), and the atmospheric-transfer-function approach (Adelson 1999a, 1999b, 2000)—predicts that figure 1 can be perceived also as a black-and-white grating behind a white veil (figure 5a) and a black veil (figure 5b). Obviously, transparency might be perceived only in the left portions of the display and not in the right, or vice versa.

The episcotister model of transparency generates two solutions for contrast-polarity-preserving T-junctions, interpreted as implicit X-junctions: one for the light veil (including targets and neighbouring portions of light top stripes); and the other for the dark veil (including targets and neighbouring portions of dark top stripes).

Recovered reflectances and transmittances of the two veils can be derived from the episcotister model of scission, by using luminances as the relevant input values and by assuming that a single homogeneous illumination is distributed over the whole display (Gerbino 1994). If T-junctions are implicit X-junctions, then the following equations relate luminances of layer regions (W and T) to luminances of background regions (I and T):

$$W = tI + (1 - t)R, \tag{1}$$

$$T = tT + (1 - t)R, \tag{2}$$

where t is the transmittance of the transparent layer (the proportion of opaque matter in the veil) and luminance R is the product of the material reflectance of the layer (the proportion of light reflected by solid sectors of the episcotister or by threads of the veil) and the common uniform illumination.

2.1 *Layer reflectance*

Equation 2 implies that $R = T$, independent of W and therefore of transmittance t. In other words, X-junctions become T-junctions whenever top stripes and the material part of the layer reflect light in the same proportion. As mentioned in section 1.1.7, a transparency-based account explains White's effect as the consequence of a perceptual shift towards recovered layer reflectances. The amount of such a shift is not defined, given that the literature on transparency does not allow us to draw firm conclusions about the independence of perceived lightness and perceived opacity of layers.

However, if both target sets are perceived as transparent veils, the episcotister model predicts that the amount of the classical White's effect will be the sum of the lightening of targets unified with light top regions and the darkening of targets unified with dark top regions.

2.2 *Layer transmittance*

From equations 1 and 2, transmittances t_{light} and t_{dark} are derived for light (IWT junctions) and dark (TWI junctions) veils respectively:

$$t_{\text{light}} = \frac{T - W}{T - I}, \tag{3}$$

$$t_{\text{dark}} = \frac{W - T}{I - T}. \tag{4}$$

Solutions for transmittance t clarify why intermediate-target patterns are always compatible with transparency. Since the numerator is smaller than the denominator and both are positive, it is always true that transmittance is a valid proportion ($0 < t < 1$).

2.3 *Finding the points of transition*

The actual perception of transparency in T-junction displays can be considered as the end result of a competition against perceived occlusion. Transparency – occlusion bistability was originally observed by Kanizsa (1955, 1979) in a display similar to figure 7, studied by Gerbino and Ripamonti (1998).

To identify points of transition between occlusion and transparency, we required observers to modify the luminance of target regions under different grating-contrast conditions.

We expected a dominance of transparency over occlusion at low values of transmittance, computed according to the episcotister model. In ecological optics, layer information is an inverse function of transmittance. Low-transmittance layers modify the pattern of background luminances more than high-transmittance layers. The same

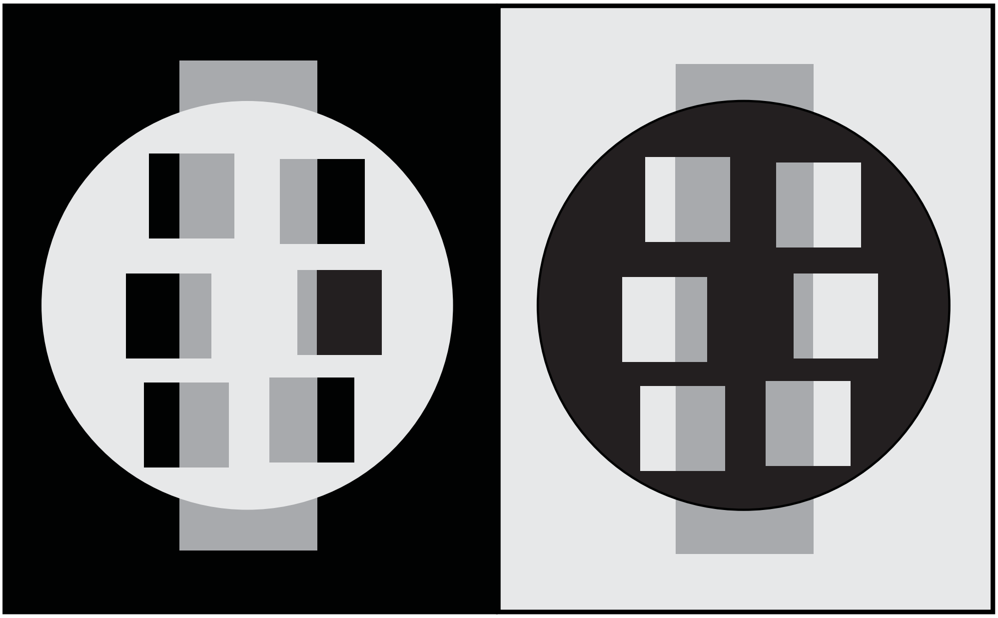


Figure 7. An analogue of figure 1 based on a demonstration by Kanizsa (1955, 1979). Local T-junction information is the same as in classical White's displays.

prediction follows from the hypothesis that the unification of targets and neighbouring portions of top regions into a single layer is favoured by luminance similarity.

Furthermore, we hypothesised that the t value corresponding to empirically determined points of transition between transparency and occlusion is independent of grating contrast. This should hold for both light and dark veils.

2.4 *Method*

2.4.1 *Participants.* Six observers (including the authors), familiar with visual psychophysics, participated in all conditions of the experimental design.

2.4.2 *Design.* In every trial observers were shown either IWT or TWI targets (veil factor) randomly located in the left or right halves of the display (position factor). Four levels of grating contrast were selected. Therefore, the within-subjects factorial design comprised 16 types of trial, one for each condition of the veil $(2) \times$ position $(2) \times$ grating contrast (4) design.

2.5 *Apparatus and stimuli*

Achromatic configurations on a blue background were generated on an ArtMedia monitor controlled by a Macintosh computer. Luminances varied within the range $1.0-55.5$ cd m^{-2}. To measure transition points for light and dark veils independently, we used a display similar to figure 1, but including either targets interrupting light stripes or targets interrupting dark stripes.

The background, obtained by activating the blue gun only (20 cd m^{-2}), subtended 20 deg $\times$ 15 deg at the 1 m viewing distance. The square-wave grating was located centrally, and subtended 18 deg $\times$ 5.14 deg. Spatial frequency was about 1.75 cycles deg^{-1} (1 cycle $\sim$ 1 cm). Each of the 6 targets was 3.7 cm wide (2.12 deg).

The following luminance pairs were selected for the grating: $32.2|9.1$; $39.4|5.3$; $47.2|2.5$; and $55.5|1.0$ cd m^{-2}. Grating average luminances (20.6, 22.3, 24.8, and 28.2 cd m^{-2}) increased slightly at increasing contrast. Grating contrast (C) was defined as the difference between power-transformed luminances (section 1.2). The resulting values of grating contrast were 3.35, 4.99, 6.61, and 8.03.

2.6 *Procedure*

The experimental session consisted of a fully randomised sequence of 64 trials (4 repetitions $\times$ 16 trial types described in the design), introduced by 3 practice trials.

In every trial the starting luminance of mid-grey targets was equal to the grating average luminance. The observer was instructed to control the target luminance by using up and down arrows on the computer keyboard and to press the space bar when the two competing percepts appeared equally probable, ie when perceiving an opaque grey surface behind occluding stripes and perceiving a transparent veil in front of a background grating were equally easy. The computer registered the final value and presented the subsequent trial. The target luminance W could vary only between T and I luminances of the current trial. Observers adapted to the procedure without any apparent effort.

2.7 *Results*

In figure 8, transition points are represented in a 2-D space with grating contrast on the abscissa and power-transformed luminance on the ordinate. The higher oblique line connects the four points representing the light stripes of the four gratings (empty squares), while the lower oblique line connects the four points representing the dark stripes of the four gratings (black squares). The task used in experiment 1 can be visualised in figure 8 by locating the point of transition between transparency and occlusion on the vertical segment connecting T and I points for any grating contrast.

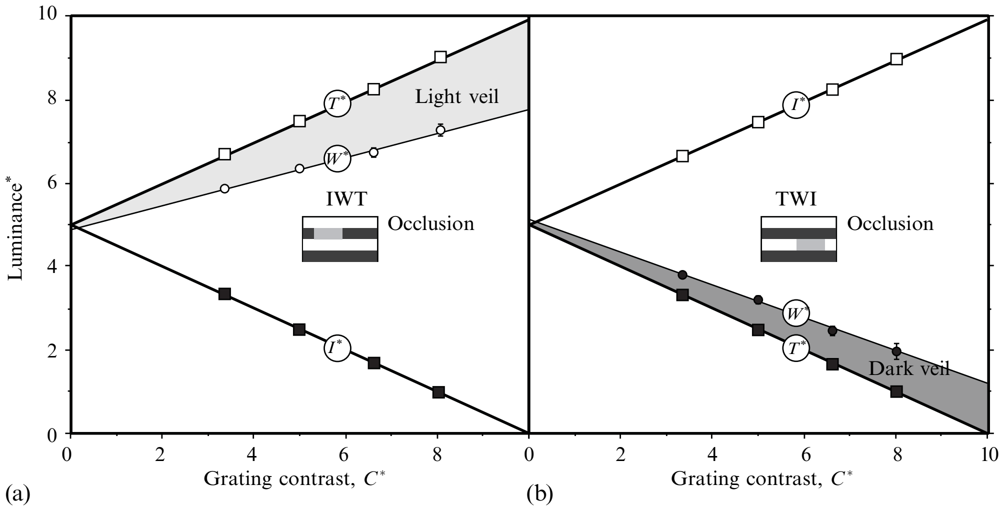


Figure 8. Power-transformed luminance space used to represent displays and data of experiment 1. Grating contrast C^*, defined as the $|T^* - I^*|$ difference, is shown on the abscissa. Grating stripes are shown on the ordinate: (a) IWT cases (I^* = solid squares; T^* = empty squares); (b) TWI cases (I^* = empty squares; T^* = solid squares). Observers adjusted the target luminance to find W_{light} (point of transition between occlusion and light-veil transparency) in IWT cases and W_{dark} (point of transition between occlusion and dark-veil transparency) in TWI cases. Mean joints of transition are represented by empty and solid circles; standard error of the mean bars are about the size of the symbol.

Mean points of transition for IWT targets are represented by empty circles (figure 8a), and those for TWI targets by full circles (figure 8b). Points of transition for light and dark veils are a linear function of grating contrast:

$$W^*_{\text{light}} = 0.29C^* + 4.90 \quad (r^2 = 0.84),$$

$$W^*_{\text{dark}} = -0.40C^* + 5.16 \quad (r^2 = 0.88).$$

The region where perception of the light veil dominates over occlusion (figure 8a) is larger than the region where perception of the dark veil dominates over occlusion (figure 8b), as shown by an ANOVA on $|T^* - W^*|$ data for the veil (2) × grating contrast (4) design. The significant main effect of veil ($F_{1,5} = 113.36$, $p < 0.001$) and the significant interaction ($F_{3,15} = 12.24$, $p < 0.001$) indicate that the light veil competes against occlusion more effectively than the dark veil.

However, such a conclusion depends on the specific transformation of luminance used to approximate the lightness scale. In the raw luminance domain, the size difference between the two transparency regions is even larger (figure 9). With logarithmically transformed luminances, the light-veil region becomes smaller than the dark-veil region. More experimental work is needed to find out whether the size difference of the two transparency regions reflects a true superiority of light over dark veils or is just a scale artifact.

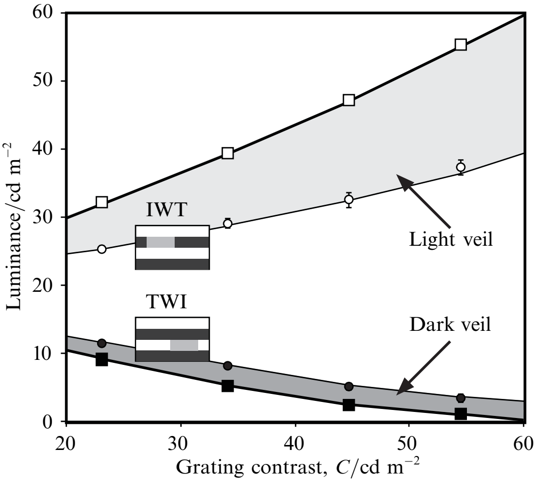


Figure 9. Transparency regions in the luminance space defined by grating contrast C (the $|T - I|$ luminance difference) on the abscissa and luminance on the ordinate. See figure 8 for symbol definitions.

We used transition points for light and dark veils to compute t_{light} and t_{dark} transmittances according to the episcotister model of transparency [equations (3) and (4)], and to test whether such values were influenced by grating contrast.

Figure 10 shows the distribution of t values for the two veils. An ANOVA on the veil (2) × grating contrast (4) design showed that the mean transmittance corresponding to the transition between occlusion and light-veil transparency was much larger than the mean transmittance corresponding to the transition between occlusion and dark-veil transparency ($t_{\text{light}} = 0.32$ versus $t_{\text{dark}} = 0.07$; $F_{1,5} = 327.25$, $p < 0.001$). No main effect of grating contrast was found ($F < 1$). The significant interaction ($F_{3,15} = 17.59$, $p < 0.001$) indicates that the two straight lines connecting t values to grating contrast differ in slope. Linear functions for light and dark veils are:

$$t_{\text{light}} = 0.001C + 0.261 \quad (r^2 = 0.11),$$

$$t_{\text{dark}} = -0.002C + 0.146 \quad (r^2 = 0.48).$$

Slope values proximal to zero suggest that the effect of grating contrast on critical transmittance is quite small. However, the significant interaction and the significance of the dark-veil slope ($F_{1,22} = 20.61$, $p < 0.001$) suggest the possible existence of the following effect of grating contrast: as contrast increases, point-of-transition transmittance increases for the light veil and decreases for the dark veil.

2.8 *Discussion*

Experiment 1 established that transparency dominates over occlusion in only two rather small regions of the triangular space representing classical White's display with intermediate-luminance targets. When transparency dominates in the IWT portion of the

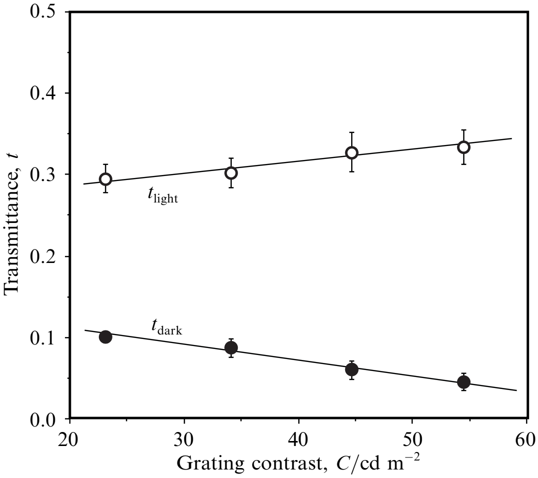


Figure 10. Transmittance values t, computed according to the episcotister model, derived from points of transition between occlusion and transparency plotted in figure 8 (experiment 1). Critical transmittance was much larger for the light veil than for the dark veil. The effect of grating contrast on critical transmittance was weak.

display (figure 1a), occlusion dominates in the TWI portion of the display (figure 1b), and vice versa. We found no luminance W favouring the perception of transparency as the preferred solution for both sets of targets in White's display.

Our data suggest that perceived transparency is an unlikely candidate as a determinant of White's effect in displays where occlusion is the dominant percept. Clearly, one can hypothesise that a transparency mechanism can affect perceived lightness even without the explicit instantiation of a perceived layer. This hypothesis cannot be easily rejected. However, if White's effect depends on transparency, one might expect the amount of effect to increase when luminance relationships favour perceived transparency. Experiment 2, in which we measured the amount of White's effect over a range of luminance combinations, does not support such a conclusion.

This is not to deny the existence of percept – percept coupling phenomena in which transparency affects lightness. The Kanizsa display in figure 7 demonstrates that the perceptual organisation of surfaces and layers is a sufficient condition for a lightness change under constant luminance conditions. Take figure 7a: when grey regions are unified into a transparent veil overlapping six black squares on a white disk, the grey becomes lighter and diaphanous relative to the hard surface colour appearance of the grey rectangle unified behind the white disk with square holes (occlusion solution). However, lightness changes associated with transparency are small compared to White's effect observed when occlusion is the dominant percept for both sets of targets.

3 Experiment 2: Amount of White's effect

In experiment 2 we studied several luminance combinations leading to classical and inverted White's effects. There is evidence that the inverted effect is weaker than the classical one (Spehar et al 1995b; Ripamonti 1996; Gerbino and Ripamonti 1997). To discover possible regularities in the direction and amount of White's effects as a function of luminance combinations, we combined 5 grey targets and 4 gratings to generate 7 intermediate-target, 4 double-increment-target, and 4 double-decrement-target configurations. The 4 gratings varied in contrast but were approximately constant in their average power-transformed luminance.

To obtain independent estimates of target lightnesses, left and right targets were matched to a set of central comparison bars in separate trials (figure 11). Observers were required to adjust the luminance of out-of-phase comparison bars, which appeared as occluders on top of the light and dark grating stripes, until they matched the targets [see Schirillo and Shevell (1996) on the matching of greys within inhomogeneous

(a) (b)

Figure 11. Observers adjusted central comparison bars appearing as occluders in front of the grating and matched them to either (a) IWT or (b) TWI targets. Actual stimuli used in experiment 2 included 9-cycle gratings and 6-element targets. White's displays shown in this figure are symbolic.

surrounds]. This procedure allowed us to evaluate the contribution of each lightness deviation to the overall White's effect, defined as the algebraic difference between the match with targets that interrupt dark stripes and the match with targets that interrupt light stripes.

3.1 *Method*

3.1.1 *Participants.* Eight observers familiar with visual psychophysics (including author WG) participated in the experiment as volunteers.

3.1.2 *Design.* All observers provided two adjustments for each target of the 15 configurations, for a total of 60 trials. The experiment was based on the position (2) × display (15) × target (2) × repetition (2) design. Position was the only between-subjects variable: four observers were shown targets interrupting dark stripes on the left and targets interrupting light stripes on the right; the opposite was true for the other four observers.

3.2 *Apparatus and stimuli*

Apparatus and displays were similar to those used in experiment 1. Six comparison bars identical to targets in size were added at the centre of the grating, with a 90° phase shift. In every trial the initial luminance of comparison bars was equal to the target luminance.

Three grating-luminance pairs were the same as in experiment 1: 32.2|9.1; 39.4|5.3; 55.5|1.0 cd m^{-2}. The fourth pair was 25.4|13.8 cd m^{-2}, with an average luminance of 19.6 cd m^{-2} and a 1.67 grating contrast (difference between power-transformed luminances). Five target luminances were selected (3.9, 10.5, 19.2, 30.3, and 43.1 cd m^{-2}), corresponding to power-transformed values of 2.11, 3.63, 5.05, 6.48, and 7.86.

Table 1 illustrates the distribution of the 15 experimental displays within the complete matrix of 5 targets × 5 grating contrasts.

3.3 *Procedure*

A different random sequence of 30 conditions resulting from display × target combinations was generated for every observer. The experimental session was introduced by a short instruction, based on 3 training trials. Using up and down arrows of the computer keyboard, the observer could modify the luminance of comparison bars and match them to the left or right targets, depending on the specific trial. The comparison bar luminance could vary between minimum and maximum values available on the monitor. The observer pressed the space bar when the difference between targets and comparison bars was minimised. The computer registered the final luminance of the comparison bars and presented the next trial. Observers adapted to the procedure without any apparent effort.

Table 1. White's displays studied in experiment 2. Shadowed cells represent combinations of target W^* and grating contrast $|T^* - I^*|$ values (in power-transformed luminance units).

W^*	$\lvert T^* - I^* \rvert$			
	1.67	3.35	4.99	8.03
7.86	■	■	■	■
6.48	■		■	
5.05	■		■	■
3.63	■		■	
2.11	■	■	■	■

3.4 *Results*

Deviations from objective values (in power-transformed luminance units) were analysed separately for intermediate-target versus double-increment-target and double-decrement-target cases.

3.4.1 *Intermediate-target displays.* Mean deviations from objective values (M) and their respective standard error of the mean (SEM) bars, are displayed in figure 12. Every plotted value is the mean of 16 adjustments (2 repetitions $\times$ 8 observers, irrespective of left/right position). In all intermediate-target displays we obtained an effect in the classical direction.

All deviations from objective values were in the direction of assimilation with top stripes and/or contrast with interrupted stripes. Deviations were positive for IWT targets ($M = 0.68$, $\text{SEM} = 0.09$) and negative for TWI targets ($M = -0.66$, $\text{SEM} = 0.06$). Mean deviations, irrespective of sign, did not differ ($t_{55} = 0.32$, $p = 0.75$, two-tailed).

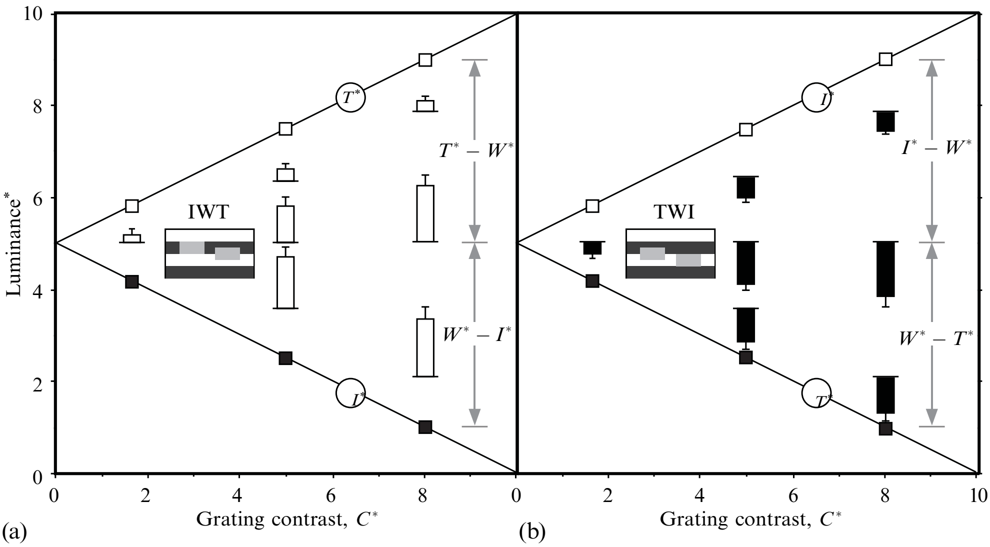


Figure 12. Mean deviations from objective values (and SEM) for (a) IWT and (b) TWI targets, in intermediate-target cases of experiment 2. The same power-transformed luminance space in figure 8 is used here. The amount of White's effect is the sum of white and black bars, indicating that targets appeared (a) lighter or (b) darker than comparison bars. All effects are in the classical direction.

This result is incompatible with any explanation, like the one based on anchoring and belongingness (Gilchrist et al 1999), that attributes White's effect to a lightness illusion for one set of targets only. It suggests that the classical effect depends on the synergy of the two components.

The overall amount of the classical White's effect (the algebraic difference of deviations in IWT and TWI cases) ranged from 0.42 (SEM = 0.23) in the 5.05|1.67 case to 2.34 (SEM = 0.42) in the 5.05|8.03 case. The mean value of 1.34 was significantly larger than zero ($t_{55} = 10.05$, $p < 0.001$, one-tailed).

To describe the pattern of deviations from objective values in intermediate-target cases, we performed a multiple-regression analysis using the amount of deviation as the dependent variable and $|W^* - T^*|$ and $|W^* - I^*|$ distances as predictors.

First, we analysed IWT and TWI cases separately. The most important variable is $|W^* - T^*|$ (ie the distance between target and top stripes), which explains 39.0% and 17.1% of the total variance in IWT and TWI cases, respectively. The inclusion of the other predictor $|W^* - I^*|$ adds only a marginal 0.6% (IWT case) and 2.0% (TWI case) to the total explained variance.

The outcome of such partial analyses is confirmed by the multiple-regression analysis on all deviations Δ ($N = 112$, 8 observers $\times$ 7 cases $\times$ 2 targets). The following equation explains 28.1% of the total variance ($F_{2,109} = 21.32$, $p < 0.001$):

$$\Delta = 0.214 + 0.153\,|W^* - T^*| + 0.004\,|W^* - I^*|\,. \qquad (5)$$

The $|W^* - T^*|$ difference accounts for all explained variance. No additional variance is accounted for by the $|W^* - I^*|$ difference. The analysis of residuals suggests that equation (5) fits the observed data adequately ($F < 0.001$).

Figure 13 provides a synthetic visualisation of data already plotted in figure 12. Deviations were averaged over four levels of $|W^* - T^*|$ and $|W^* - I^*|$ distances. The amount of deviation is represented by the area of the symbol for every display. The graph makes it clear that the lightness illusion increases along the abscissa, as the luminance distance between targets and top stripes increases; no comparable change occurs as a function of the luminance distance between targets and interrupting stripes.

Equation (5) indicates that target-lightness deviations measured in experiment 2 result from two additive components: a variable component, dependent on the distance between target and top stripes on the luminance continuum; and a constant component.

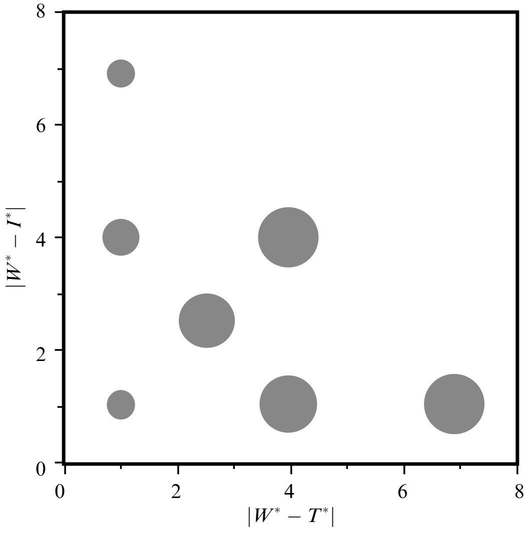


Figure 13. Pooled deviations in 7 positions of the $|W^* - T^*| \times |W^* - I^*|$ space. The amount of deviation is represented by the area of the disk used as a symbol (in power-transformed luminance units, as indicated in the insert). The graph displays the results of the multiple-regression analysis. We suggest that the classical White's effect results from the synergy of assimilation with top stripes (increasing as the target–top-stripe luminance distance increases) and contrast with interrupted stripes (constant).

The other variable component, dependent on the luminance distance between targets and interrupted stripes, is negligible.

As regards the significant variable component, we suggest that it is the amount of assimilation to top stripes, which increases at larger distances on the luminance continuum. Note that a similar effect of luminance distance has been found in SLC by Economou et al (1999). Their anchoring account predicts a luminance distance effect in IWT but not in TWI cases of White's display.

In principle, both assimilation to top stripes and contrast with interrupted stripes are possible candidates for the constant component, independent of distance on the luminance continuum. However, on the basis of general evidence on selective contrast effects we hypothesise that the constant component in equation (5) is contrast.

3.4.2 *Double-increment-target and double-decrement-target displays.* In 15 out of 16 conditions, deviations from objective values were opposite in direction to those obtained in intermediate-target conditions, in the sense that targets interrupting dark stripes appeared darker, and targets interrupting light stripes appeared lighter, than comparison bars. The mean deviation in double-increment cases did not differ from the mean deviation in double-decrement cases ($F < 1$). Figure 14 shows the pattern of data for the inverted White's effect.

An inverted White's effect (always defined as the algebraic difference between the two deviations) was obtained in 3 out of 4 double-increment-target displays and in 4 out of 4 double-decrement-target displays. The inverted effect was smaller than the classical effect obtained with intermediate targets, but significantly different from zero (0.13, SEM $= 0.04$; $t_{63} = -3.49$, $p < 0.001$, one-tailed).

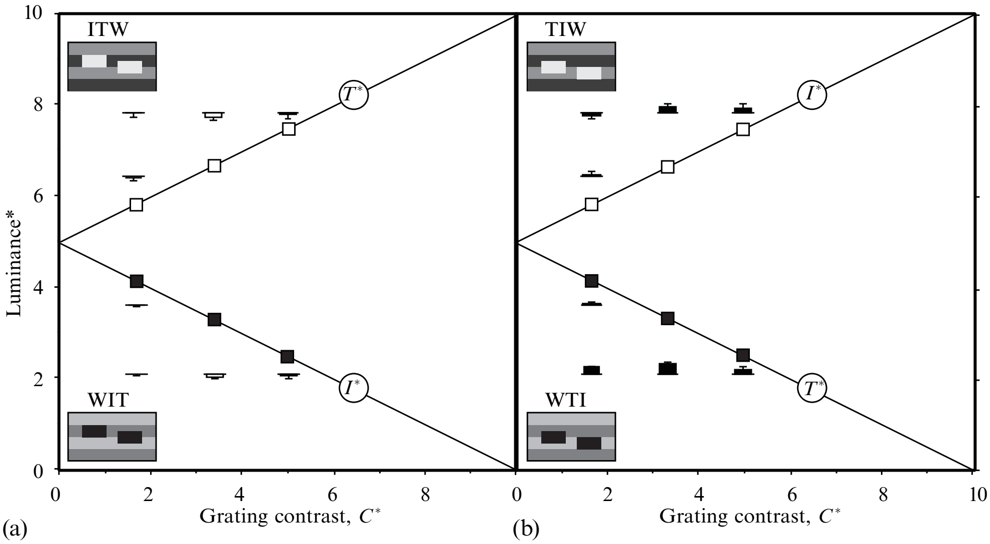


Figure 14. Mean deviations from objective values (and SEM) for double-increment-target (upper triangles) and double-decrement-target (lower triangles) cases. A small inverse effect is obtained. Notice that double-increment ITW cases (upper left) and double-decrement WTI cases (lower right) are symmetrical: the luminance order in the display as well as the direction of the effect are reversed. The same is true for the reversal between double-increment TIW cases (upper right) and double-decrement WIT cases (lower left).

3.5 *Discussion*

Our analysis suggests that White's effect in classical displays with intermediate-luminance targets depends on the synergy of two factors: assimilation to the top stripe and contrast with the interrupted stripe. In this context, assimilation and contrast simply describe the direction of elementary effects, not specific mechanisms. As such they are compatible with several of the mechanisms described in the introduction. Assimilation might be of the von Bezold type, or might depend on layer analysis and transparency. Contrast might be a byproduct of figure–ground organisation, or might depend on colour–illumination invariance. However, we claim that the large deviations obtained in intermediate-target displays reflect the cooperation of both effects (figure 15).

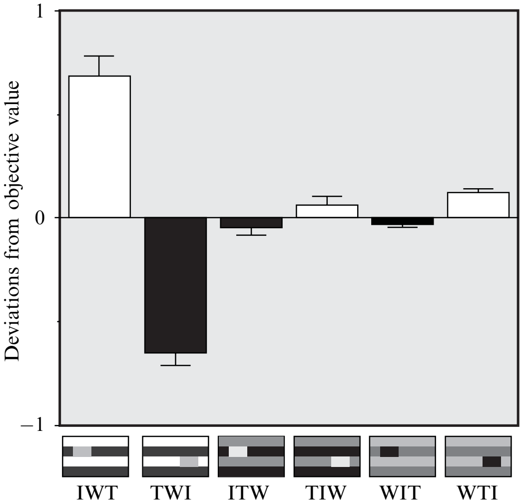


Figure 15. Mean deviations (and SEM) for each of the 6 types of target/grating combination used in experiment 2.

In double-increment-target and double-decrement-target displays, assimilation to top stripes and contrast with interrupted stripes can explain the inverted effect under an additional constraint—luminance adjacency. The pattern of deviations in ITW, TIW, WIT, and WTI conditions indicates that the effect is always in the direction of either assimilation to or contrast with the region that is adjacent to the target on the luminance continuum. Conditions ITW and WTI are similar because the relevant effect is assimilation to the top stripe. Conditions TIW and WIT are similar because the relevant effect is contrast with the interrupted stripe. As shown in figures 14 and 15, this regularity results in the darkening of ITW and WIT targets, as well as in the lightening of TIW and WIT targets.

In intermediate-target cases the principle of luminance adjacency predicts the cooperation of assimilation and contrast, because the target luminance is flanked by both top-stripe and interrupted-stripe luminances.

4 Conclusions

In experiment 1 we tested the hypothesis that White's effect depends on the formation of a transparent layer. All intermediate-target displays contain only T-junctions that preserve contrast polarity. Therefore they are always compatible with a transparency solution according to the episcotister model (Metelli 1970, 1974; Beck et al 1984; Gerbino et al 1990; Gerbino 1994), as well as with the scission mechanism described by Anderson (1997). According to the episcotister model, White's effect depends on the target being shifted towards the perceived reflectance of the unitary layer. According to Anderson's scission mechanism, the effect depends on the target being shifted away from the interrupted stripe, as a residual of the extraction of a common component equivalent to the interrupted-stripe luminance.

Results of experiment 1 indicate that perceived transparency prevails over the alternative occlusion solution in only two rather small regions of the stimulus domain that includes all intermediate-target displays (the central triangle in figures 8 and 12).

Outside such regions, transparency may be perceived but is not a spontaneous perceptual solution, as shown by the remarkably low variability of point-of-transition adjustments. The occurrence of perceived transparency followed a regular pattern, constrained by the value of transmittance *t*, which was computed according to the episcotister model.

We agree that, when target and top-stripe luminances are very similar, White's effect might be reinforced by the perception of a low-transmittance layer comprising one set of targets and neighbouring portions of top stripes. For instance, displays like figure 1 elicit the perception of a light veil on the left when targets are close to white and of a dark veil on the right when targets are close to black. The different appearances of the lightness of a transparent veil and the lightness of an amodally completed opaque rectangle might increase the salience of White's effect.

To explain White's effect, transparency could be invoked as a general mechanism, affecting lightness independently of the actual perception of a superposed layer. However, as anticipated in the discussion of experiment 1 (section 2.8), we think that this hypothesis should at least imply a correlation between the amount of the lightness deviation and the likelihood of perceiving a transparent layer. Experiment 2 provided no evidence of such a correlation. Deviations increase as a direct function of the luminance distance between the target and the top stripe, whereas perceived transparency is more likely at small target – top-stripe luminance distances (figure 8).

In experiment 2 we measured White's effect in intermediate-target, double-increment-target, and double-decrement-target displays, asking our observers to adjust comparison bars superposed on the grating. The most salient result is the inversion of lightness deviations in double-increment-target and double-decrement-target cases, relative to those obtained in classical intermediate-target cases.

In our unitary explanation of classical and inverted White's effects, the formation of a single layer comprising targets and portions of top stripes is not necessary. Assimilation and contrast depend only on the luminance ordering of the three regions meeting at T-junctions, not on the organisation of regions into higher-order entities and 3-D scene interpretation.

Recently, we studied Munker's effect (Schober and Munker 1967; Taya et al 1995), the chromatic antecedent of White's effect (Ripamonti et al 1998; Plet et al 2000). We found evidence that Munker's effect involves both assimilation and contrast, and we confirmed a conjecture by Gerbino and Kanizsa (1987) about their selectivity: assimilation mainly occurs in the hue domain (including the qualitative appearance of black and white) and contrast only occurs in the intensity domain. Achromatic White's displays studied in experiment 2 also involve both assimilation and contrast. This is consistent with the contrast/assimilation paradox described by Kanizsa (1954, 1979) and with other observations, including the reports of qualitative differences within the achromatic domain of White's displays (Anderson 1997, discussion of his figure 10).

Three principles account for the pattern of data on classical (figure 12) and inverted (figure 14) White's effects. Such principles predict the lightness match of targets that interrupt one set of grating stripes, generating T-junctions in which targets and interrupted stripes straddle the T-stems, with comparison bars locally identifiable as the top regions of T-junctions in which grating stripes straddle the T-stems (figure 11).

At T-junctions:

- targets deviate towards top stripes (assimilation);
- targets deviate away from interrupted stripes (contrast);
- assimilation and contrast occur only if the stripe luminance is adjacent to the target luminance (luminance adjacency).

According to our analysis, these principles capture the selectivity of lightness effects at T-junctions. The direction of each effect (either towards or away from a spatially adjacent region) depends on the spatial structure: assimilation to the top region versus contrast with the interrupted region. The occurrence of each effect depends on the photometric structure: a given region acts as an effective inducer only if its luminance is adjacent to the target luminance.

Both T-junction constraints can be related to belongingness, ie to the modulation of effects as a function of the degree of unification of parts. The spatial structure of T-junctions determines a stronger unification across the T-stem than across the top edge of the T. The photometric structure determines the strong unification of regions with similar luminances and the relative isolation of regions separated by an intervening region along the luminance continuum.

The results of experiment 2 can be compared to previous data obtained with a different method. In a previous study (Gerbino and Ripamonti 1997) we used a 4 cycles $\deg^{-1}$ grating and measured classical and inverted White's effects by asking observers to match targets with patches approximating a Munsell scale (14 greys of a power-transformed luminance scale, on a common white background). Observers had to choose the 2 grey patches that most resembled 2 simultaneously visible targets of White's display. Grating contrast was varied by changing the luminance of the lighter stripe and keeping the darker stripe at the same minimum-luminance value; 5 intermediate-target cases and 4 double-increment cases were tested. In these conditions, large classical and inverted White's effects were measured.

To compare the amount of White's effect in intermediate-target cases obtained in the present study (experiment 2) and in our previous measurements (Gerbino and Ripamonti 1997), we used equation (5) to compute a set of expected values for our 5 previous intermediate-target cases. In figure 16, mean differences between obtained and expected amounts are plotted against expected values, shown on the abscissa. Effect amounts obtained in the previous study were always larger than expected on the basis of equation (5), derived from the present study. The mean difference between obtained and expected White's effect amounts was equal to 0.307 ($t_{64} = 4.54$, $p < 0.001$). Analysis of residuals suggests that equation (5) cannot fully account for our earlier data. An additional 6.5% of the variance is explained by a second-order polynomial regression of residuals over expected values ($F_{1,63} = 4.37$, $p < 0.05$).

The large White's effect previously measured by us (Gerbino and Ripamonti 1997) can be attributed to three possible causes: (i) the higher spatial frequency of the grating; (ii) the matching procedure, based on the reproduction of the overall amount of White's effect, and not on independent adjustments for each target like in the present study;

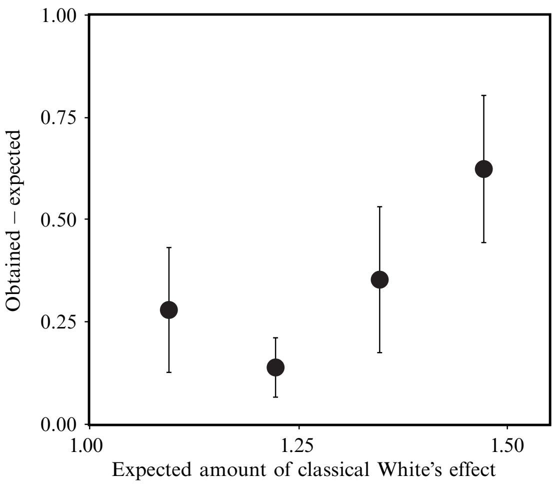


Figure 16. Analysis of the 5 intermediate-target cases previously studied by us (Gerbino and Ripamonti 1997). Expected values were computed with equation (5) derived from the present experiment 2. In two cases the expected amount was the same (1.222). Mean differences between obtained and expected amounts of the classical White's effect (and SEM) are plotted against the expected amounts. Classical White's effects measured previously were always larger than predicted by equation (5).

(iii) the use of a lightness scale on a common white background. The first cause is quite plausible if White's effect depends also on von Bezold's assimilation, which is stronger at higher spatial frequencies. However, a direct test is necessary to establish how spatial frequency affects White's effect.

Interestingly, we (Gerbino and Ripamonti 1997) also obtained an inverted White's effect ($M = 0.62$, SEM $= 0.08$) larger than the one obtained in the present experiment 2 ($M = 0.10$, SEM $= 0.07$). Both mean amounts refer to the average of data from 4 target – grating combinations.

The fact that previously measured effects were larger than those obtained in experiment 2 fits the present explanation. Given that effects obtained in the three types of displays (with intermediate targets, double-increment targets, and double-decrement targets) are explained by the same principles, factors that increase the amount of effect in intermediate-target cases should produce a similar increase in other cases as well.

If our explanation of classical and inverted White's effect is correct, then the dichotomy suggested by the two names might lose its justification. Temporarily, it can be maintained because it is useful at a descriptive level. It might be abandoned in favour of a better qualification if the general account provided by the principle of luminance adjacency is supported by future experiments.

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