Conditions for Perceptual Transparency

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Abstract

We review the conditions that are necessary for the perception of transparency and describe the spatiochromatic constraints for achromatic[1] and chromatic[2] transparent displays. These constraints can be represented by the convergence model and are supported by psychophysical data[3]. We present an alternative representation of the constraints necessary for transparency perception that is based on an analogy with a model of colour constancy and the invariance of cone-excitation ratios[4]. Recent psychophysical experiments are described that suggest that displays where the cone-excitation ratios are invariant produce a stronger impression of transparency than displays where the cone excitations are convergent. We argue that the spatial relations in an image are preserved when a Mondrian-like surface is partially covered by a transparent filter and therefore show an intriguing link between transparency perception and colour constancy. Finally, we describe experiments to relate the strength of the transparency percept with the number of unique patches in the image display. We find that the greater the number of surfaces in the display that are partially covered by a transparent filter the stronger the impression of transparency.

Keywords: transparency, colour constancy, cone excitations, spatial vision, image complexity.

1. Introduction

In this study we conduct two psychophysical experiments to investigate whether invariant cone-excitation ratios predict the *perception* of transparency. In one experiment we quantitatively compare the strength of the transparency percept for stimuli defined by the invariant cone-excitation-ratio condition with stimuli defined by the convergence model[3]. In a second experiment stimuli were presented that simulated Mondrian surfaces partially covered by a transparent filter and the effect of the number of partially covered surfaces in the display was measured in terms of the strength of the transparency percept.

Perceptual transparency is the phenomenon of seeing one surface behind another. For example, in Figure 1 four opaque areas give rise to the perception of two opaque surfaces (large rectangles) seen behind a transparent filter (small rectangles). Many authors[5,6] have stated that the filtered region is the area where we can simultaneously perceive both the filter and the opaque surface behind the filter. However, recovering the colour of two surfaces from one set of strictly local cone excitations would seem to be intractable. Furthermore, if an opaque surface is partially covered by a filter whose colour is complementary (for example, a red surface and a green filter) the filtered patch will appear very dark and the red and green surfaces do not seem to be simultaneously observed[2].
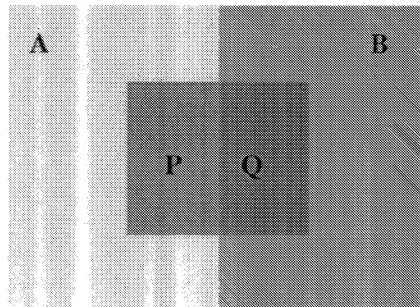

Figure 1. Two opaque surfaces covered by a homogeneous transparent filter. A and B are opaque surfaces and P and Q the corresponding filtered areas.

The first quantitative model of the photometric constraints for transparency perception was Metelli's *episcotister* model[1,6]. The episcotister is a wheel with open sectors rotating in front of two opaque surfaces. During its rotation the episcotister colour is perceived to be a fusion colour between its sector colour and the background colour. According to Metelli, in order to perceive transparency two photometric constraints must be preserved. Specifically, the PQ region (see Figure 1) will be perceived to be transparent when

- the difference $|(a - b)|$ is greater than the difference $|(p - q)|$, thus, $|(a - b)| > |(p - q)|$;
- the direction of contrast is the same, thus, if $|(a > b)|$ then $|(p > q)|$

where a, b, p, and q are the reflectances of the areas A, B, P and Q respectively (see Figure 1).

Photometric conditions, and more generally chromatic conditions (we use the term chromatic quite generally to imply constraints on the colour of stimuli) are necessary but not sufficient for perceiving transparency. Metelli[1,6] proposed three main figural conditions that are also necessary for transparency perception: figural unity of the transparent region, continuity of the boundary line, and adequate stratification. Recent studies have proposed some additional constraints for the perception of transparency. It has been conjectured that the presence of X-junctions formed by the junctions of borders of opaque surfaces and transparent medium at the overlapping area is a necessary element in the image[7-9]. In order to have an X-junction a minimum of four areas is needed. However, other studies have shown that even with only three areas perceptual transparency occurs[10].

1.1 The convergence model

The episcotister model has been adopted more or less in its original formulation by most of the researchers investigating transparency. Minor changes have been suggested. For example, Gerbino *et al.* proposed[11] that the computations carried out by the visual system when perceiving transparency might be in terms of luminance values rather than reflectance values[1] or lightness values[12].

The perception of coloured stimuli was studied[2,13] to generalize Metelli's results with achromatic additive colour mixture to the three dimensions of colour space. Faul investigated the conditions under which transparency perception held and demonstrated that both luminance and chromatic constraints were necessary[13]. Although luminance relationships may be necessary for the perception of transparency in achromatic images, they are not sufficient when the objects in the image do not have the same chromaticities. In fact, it has been shown[3,14] that the perception of transparency holds even when opaque and filtered surfaces have identical luminance and differ only in their chromaticities. Whereas Faul treated luminance and chromatic constraints separately in his models[13], D'Zmura *et al.* considered the overall effect of lumianace and chromatic constraints and suggested that some tristimulus representation of the colours of the filtered surfaces must converge to a point in colour space. They show evidence that subjects are able to adjust the colour of a filtered surface in order to make the central region appear transparent. For example, if the tristimulus values of two opaque surfaces A and B are given by x_A and x_B respectively the adjusted colours would lie on lines passing through x_A and g, and x_B and g, respectively, where g defines the tristimulus values of the convergence point.

The convergence model can be expressed by the following equations

$$x_P = (1-\alpha)x_A + \alpha g \tag{1}$$

$$x_Q = (1-\alpha)x_B + \alpha g \tag{2}$$

where α defines the amount by which the surface colours x_A and x_B are shifted towards the convergence point g.

The performance of the convergence model has been compared with other models – including models based on cone scaling such as von Kries – and has been quantitatively demonstrated to fit the colour shifts that correspond to transparency better than the other models[15]. More recently it has also been shown that the convergence model can also account for the colour changes that take place when surfaces are viewed through a fog[16].

The convergence model defines chromatic conditions under which transparency perception can occur. The approach that we adopt similarly defines chromatic conditions for transparency perception and is broadly consistent with the

convergence model. Our approach was inspired by a simple computational model of colour constancy based upon the invariance of cone-excitation ratios[4].

1.2 Invariance of cone-excitation ratios

Perception of transparency poses the general question of how the visual system can correctly recognise the colour of a surface when its colour has been altered in some way by, for example, covering a surface by a transparent filter. An analogous problem has been investigated in colour constancy: when the colour signal of a surface is altered by illuminating it with a different light source its colour appearance remains approximately constant (although the physical constraints upon the colour signals introduced are different when the illumination is changed than when the surfaces are partially covered by a transparent filter).

In the case of a change in the illumination it has been found that, within each cone class, cone-excitation ratios between surfaces seen under one illuminant and cone-excitation ratios for the same surfaces seen under another illuminant are almost invariant and this may be a cue for colour constancy[4]. In the perception of transparency case we make the same predictions since certain changes to the illuminant are approximately equivalent to passing the illuminant through a transparent filter.

The principle of invariance of cone-excitation ratios states that the ratios of the cone excitations between two opaque surfaces and the ratios between the same surfaces covered by a filter are almost statistically invariant within each cone class. This can be expressed by the equation

$$e_{i,1}/e_{i,2} = e'_{i,1}/e'_{i,2} \qquad\qquad (3)$$

where the cone excitation is given by $e_{i,j}$ for cone class i (where $i \in \{L, M, S\}$ denoting long-, medium-, and short-wavelength-sensitive cone classes) for a surface j seen directly and the prime superscript denotes the excitations for the surface viewed through a filter. For many conditions the predictions made by the invariance model (Equation 3) and by the convergence model (Equations 1 and 2) are very similar[17]. This is not surprising since the two models are mathematically identical if the convergence model assumes no additive component ($g = 0$, Equations 1 and 2) and if the cone-excitation ratios are equal to α for all three cone classes (Equation 3). Clearly, the two models could give different predictions when these strict conditions are not met.

It is important to note, however, that the hypothesis that perceptual transparency can be predicted by the invariance of cone-excitation ratios does not rely upon such ratios being invariant for all physically transparent systems. Indeed, it relies upon such ratios not being close to being invariant for some physically transparent systems since not all physically transparent systems are perceptually transparent[6]. In a previous study[18] we conducted a Monte Carlo simulation and showed that, although the cone-excitation ratios were close to invariance for some physically transparent systems, the invariance was poor for filters with narrow-band spectral transmission properties. Furthermore the model for physical transparency used in that previous study was a simple model that did not, for example, include a component of specular reflectance. It is likely that we would have found further deviations from invariance had we used a more realistic model. We do not state that the cone-excitation ratios would be exactly invariant for either physically or perceptually transparent systems. The key issue that needs to be addressed is whether the degree of invariance of the cone-excitation ratios for psychophysical stimuli can predict the strength of the transparency percept when those stimuli are viewed.

2. Experiment 1

2.1 Aims

In the first experiment we simulated *invariant* stimuli where the colours produced by the overlay of a Mondrian surface by a transparent filter were defined by the invariance of the cone-excitation ratios and *convergent* stimuli where the colours were defined by the convergence model. The pairs of stimuli were presented side by side to observers who were asked to respond which of the two stimuli contained the most transparent filter. The purpose of the experiment was to ascertain whether the invariant model or the convergence model best predicts the strength of the transparency percept.

2.2 Methods

Stimuli contained Mondrian patterns (4.52 × 3.58 degrees of visual angle) composed of 12 surfaces displayed in a 12 x 6 arrangement and partially covered by simulated transparent filters (3.38 × 0.95 *deg*). The filters were generated using the convergence model. The *convergent* stimuli were compared with *invariant* stimuli where the Mondrian patterns were partially covered by a simulated transparent filter whose cone-excitation ratios were systematically made invariant. For each convergent stimulus the colours of the transparent areas were modified to make the cone-excitation ratios perfectly invariant. For each of the convergent stimuli the parameter α was randomly selected from the values 0.1, 0.3, 0.5, 0.7 and 0.9 and one of five randomly selected **g** points were used (Equations 1 and 2). Figure 2 shows a schematic representation of the stimulus patterns.
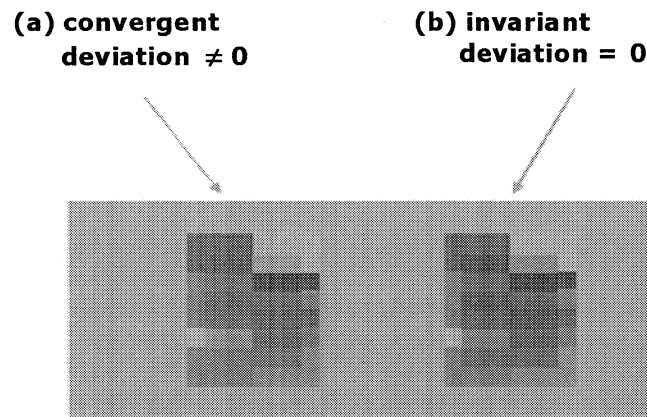

Figure 2. Schematic representation of the stimulus patterns used in Experiment 1.

In each trial the two stimulus patterns (the one covered by the convergent filter and the one covered by the invariant filter) were presented simultaneously side by side (Figure 2). The invariant filter could randomly appear either on the left- or on the right-hand side. In a 2-alternative-forced-choice (2AFC) paradigm six observers were asked which of the two stimulus patterns simulated a uniform transparent filter over opaque surfaces. Each presentation lasted two seconds on screen. The inter-stimulus interval lasted one second. The next trial was presented two seconds after the subject indicated their response with a button press. Each trial was repeated 3 times for a total of 150 trials (3 (repetition) × 2 (left or right position of the invariant filter) × 5 (α) × 5 (**g**)).

2.3 Results

For each trial we calculated the degree of deviation from invariance in spatial cone–excitation ratios for all the possible pairs of surfaces seen directly and under the filter displayed in each image. The degree of deviation was equal to

deviation = $1 - r_i$ if $r_i \leq 1$

deviation = $1 - 1/r_i$ if $r_i > 1$ (4)

where r_i is the ratio of cone-excitation ratios defined as

$r_i = (e_{i,1}/e_{i,2}) / (e_{i,1}'/e_{i,2}')$.   (5)

Note that for the invariant filters the deviations were always exactly zero whereas for the convergence filters the deviations varied between 0 and 0.2 (for some trials the convergence model generated stimuli whose ratios were already invariant or close to being invariant and in these cases the deviations for the two classes of stimuli were very similar; for other trials the deviations for the convergence model were quite large and the two classes of stimuli were quite different). Subjects' performance in the task was measured by *d prime* (d') where positive values of d' indicate a preference for the invariant filter, negative values indicate a preference for the convergent filter, and chance performance is indicated by $d' = 0$. Figure 3 shows that observers generally preferred the invariant filter to the convergent filter (positive values of d'). However, we found no significant preference ($d' = 0$) when the convergence filter had deviations close to 0. Negative values of d' represent subjects' preference for the convergent filter; however, they were not significantly different from 0 (chance performance).
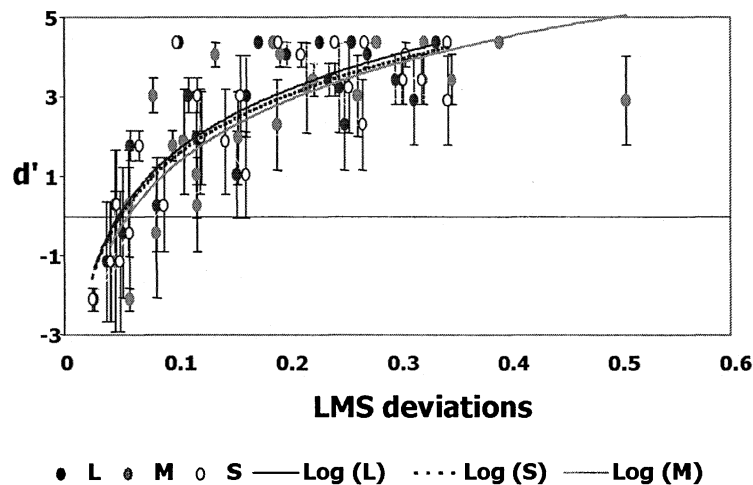

Figure 3. $d' < 0$ indicates subjects' preference for convergent filter; $d' = 0$ no preference; d' > 0 indicates subjects' preference for invariant filter.

3. Experiment 2

3.1 Aims

In the second experiment we investigated the effect of the number of surfaces in a Mondrian display partially covered by a transparent filter on the transparency percept. We simulated *invariant* stimuli where the colours produced by the overlay of a Mondrian surface by a transparent filter were defined by the invariance of the cone-excitation ratios and noisy *comparison* stimuli where noise was added to the cone excitations to perturb the invariance. The pairs of stimuli were presented simultaneously to observers who were asked to respond which of the two stimuli contained a homogeneous transparent filter. The purpose of the experiment was to ascertain whether image complexity influences the transparency perception. An earlier study by Da Pos and Izzinoso has shown that image complexity affects perceptual transparency; in particular, the greater the image complexity the stronger the transparency perception[19].

3.2 Methods

Stimuli contained Mondrian patterns (4.52 × 3.58 degrees of visual angle) composed of 2, 4, 6, or 8 surfaces partially covered by simulated transparent filters (3.38 × 0.95 *deg*). The colours of the filters were generated using a simple physical model of transparency[18] and the parameters of the model were selected so that the stimuli were perceptually transparent. The cone-excitation ratios in these *physical* stimuli were not exactly invariant but were always close to invariance. These stimuli were compared with noisy *comparison* stimuli where the colours of each transparent patch were subject to up to 4% noise. In each trial the two stimulus patterns (the one covered by the physical filter and the one covered by the comparison filter) were presented sequentially in random order (Figure 4). In a 2-alternative-forced-choice (2AFC) paradigm three observers were asked which of the two stimulus patterns simulated a uniform transparent filter over opaque surfaces. Each presentation lasted two seconds on screen. The

inter-stimulus interval lasted one second. The next trial was presented two seconds after the subject indicated their response with a button press. Each trial was repeated three times for a total of 168 trials (3 (repetitions) × 7 (combinations of cone-classes perturbed) × 4 (number of surfaces) × 2 (randomised presentation order)). The complete session of 168 trials was repeated twice. A training run of twenty trials was given before each session and subsequently discarded. No feedback was provided during the experiment.

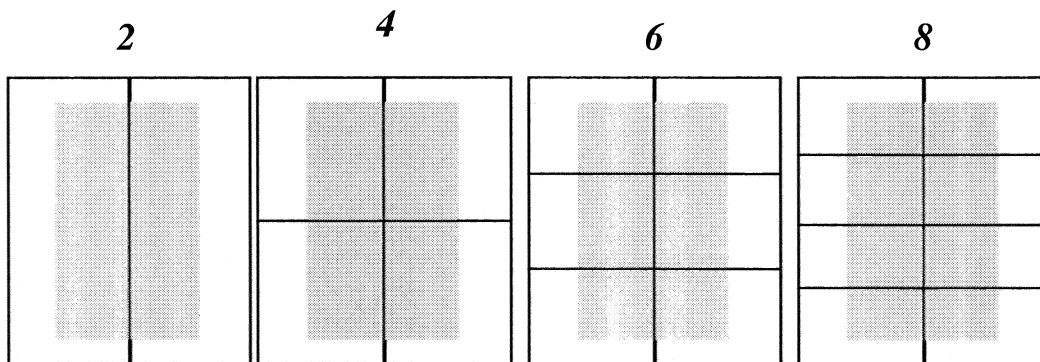## *number of opaque surfaces in the image*

Figure 4. Schematic representation of stimuli used in the Experiment 2. Stimuli varied according to the number of opaque surfaces (2, 4, 6, and 8) present in each image. Lighter areas represent opaque surfaces, darker areas represent transparent filters.

3.5 Results

Performance was quantified by d' where values of d' equal to zero indicate chance performance (d' greater than zero indicates preference for the physically plausible filter; d' less than zero indicates preference for the comparison). Figure 5 illustrates d' means versus the number of surfaces in the Mondrian display. From Figure 5 it is perhaps surprising that discrimination performance is relatively poor when only two Mondrian surfaces were partially covered by a transparent filter; previously it has been suggested that at least two surfaces are required for transparency perception[6]. However, in this experiment we did not test whether a stimulus looked transparent or not, but rather whether observers were able to discriminate the strength of the transparency percept of stimuli that were approximately invariant and those that were noisy. It is evident from the figure, however, that discrimination is reliable for four or more surfaces, but that discrimination performance generally improves with the number of surfaces.
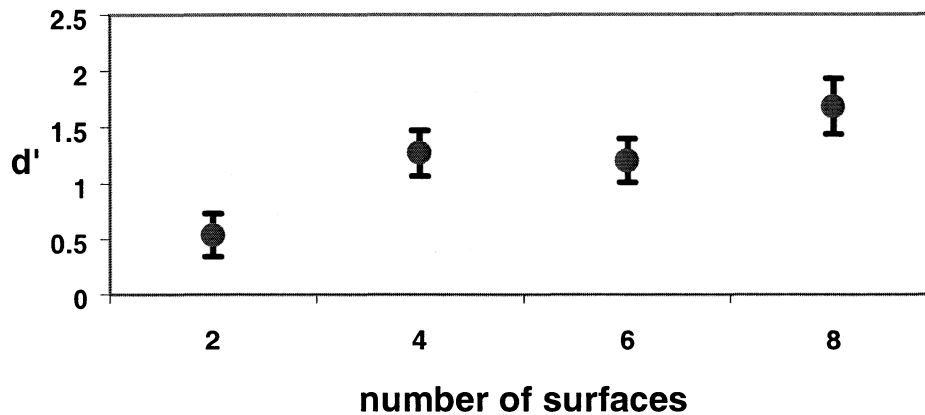
Figure 5. Results of Experiment 2. Mean values of d' as function of number of surfaces composing Mondrian patterns.

4. Discussion

We have demonstrated that the human visual system is able, under certain constraints, to separate the colour properties of the transparent filter from the colour properties of the underlying surfaces, and thus recognise surfaces seen through the filter as belonging to those surfaces seen in plain view. However, we do not suggest that the human visual system is able to extract the colour of the filter, merely that it is able to discriminate simulations of filtered surfaces where ratios of cone-excitations remain invariant from simulations where the cone-excitation ratios are not invariant. In a previous study[18] we used a simple model of physical transparency to show that the cone-excitation ratios for pairs of surfaces viewed directly and for the same surfaces viewed through a physically transparent filter were close to being equal in certain conditions. Although it is interesting that some physically transparent systems can be shown to have invariant cone-excitation ratios (at least to a first approximation) it is clear that such ratios will not be invariant for all physically transparent systems. This paper addresses the question of whether the invariance of cone-excitation ratios for surfaces covered by a transparent filter is a cue for perceptual transparency. Two experiments were carried out and in each experiment observers were asked to discriminate between two simulations of Mondrians partially covered by a transparent filter. Observers were asked to select which of the two stimuli simulated a homogeneous transparent filter.

In Experiment 1 we directly compared the invariance model with the convergence model and found that in most cases observers preferred the stimulus defined by the invariance model. However, this is not to say that the stimuli generated by the convergence model did not appear to be transparent. An important property of the invariance model, however, is that it can predict the degree of transparency. It is interesting that the more the convergent stimulus deviated from perfect invariance the greater the preference of the observers for the invariant stimulus.

It was noted earlier that the invariance model and the convergence model could be made identical given certain constraints to each. Given the similarity, it is reasonable that there may be a wide range of conditions for which the two models perform similarly but certain conditions where the predictions of the two models would be different. The performance of the convergence model has been quantitatively demonstrated to fit the colour shifts that correspond to transparency better than a simple cone scaling model[15]. However, we show that the invariance model makes better predictions than the convergence model for certain stimuli[17]. Thus it seems that there are stimuli that are better predicted by the convergence model whilst at the same time there are other stimuli that are better predicted by the invariance model. The convergence model contains an additive component and might be expected to make good predictions for stimuli with substantial specular reflectance. Stimuli with scattering components such

as turbid media may also be predicted well by the convergence model (however such systems would be more accurately described as translucent rather than transparent). Similarly, we might predict that the situations where the invariance model would outperform the convergence model would be those where the ratios of the cone excitations are close to invariance but are very different for each of the cone classes.

In Experiment 2 we found that in discrimination experiments between simulations of filters giving small deviations from invariance and filters giving large deviations, performance improved with the number of surfaces in the display. Our hypothesis was that with an increased number of surfaces there would be a corresponding increase in the number of pairs of surfaces from which invariant cone-excitation ratios could be recovered. For computational models of perceptual transparency that make use of X-junctions and T-junctions[8,20] the number of X-junctions also increases with the number of surfaces in the image. It is likely that the number of surfaces is one of several factors that could affect the strength of psychophysical cues for transparency; we might reasonably expect other factors to include the variance[21] of the surfaces and their spatial relationships. For real scenes we would expect many additional factors (such as surface specularity and the degree of spatial uniformity of surfaces) to be involved[22,23]. We note that Experiment 2 does not allow is to ascertain whether the enhanced performance is caused by an increased number of ratios or an increased variance in the ratios.

In conclusion, our psychophysical data support the hypothesis that invariant cone-excitation ratios may provide a cue for transparency perception. However, such invariance seems to be a necessary but not sufficient condition for transparency perception. Furthermore, the invariance constraint may not be uniquely represented as invariant cone-excitation ratios; indeed, other models (such as the convergence model[3]) may provide approximately alternative representations of the same constraint.

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