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Achromatic transparency and the role of local contours

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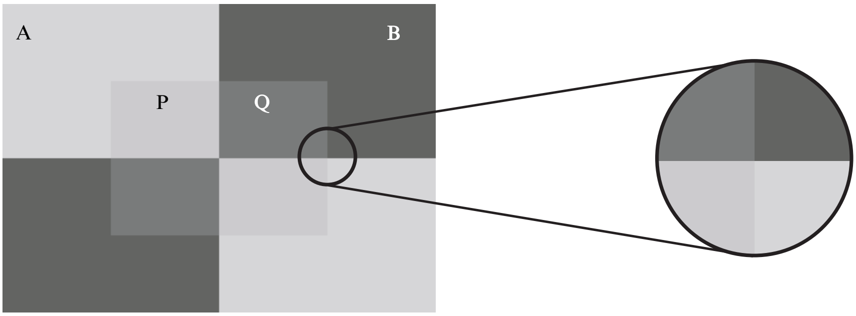
Abstract. In this paper we investigate the role of contours and junctions in the perception of single-plane achromatic transparency. In order to measure the accuracy with which observers encode transparency, a six-luminance stimulus was employed in which the figural properties could be easily manipulated. Accuracy was measured by requiring subjects to select (either by the method of adjustment or by using a forced-choice procedure) the luminance that best completed a simulated transparent filter. The X junctions in the stimulus were destroyed or perturbed in three experiments. Simple occlusion of the junction (experiment 1), and perturbation of the orientation of the contours of the filter as they pass through the junction (experiment 3) resulted in small but significant reductions in performance. On the other hand, a sudden change in orientation of the background (material) contours (experiment 2) resulted in a small but significant *enhancement* of overall performance compared with the control stimulus. In the forced-choice task, reversals in the polarity of contours (as defined by the brightness order of flanking regions) around the junction were shown to effect large changes in subjects' accuracy in processing transparency. The overall results show that X and Ψ junctions are indeed salient properties of transparent stimuli. The findings suggest that jagged contours with sudden changes in direction are more likely to be attributed to reflectance (material) changes than to changes due to a transparent filter (or to illumination).

1 Introduction

Transparency, described phenomenally as 'seeing through' surfaces, has been the subject of much recent study. Interest in transparency is motivated by more general questions regarding scene analysis. Transparency can be thought of as belonging to a broader class of illumination effects, including shadows and highlights (both limiting cases of transparency), which cause abrupt changes in image luminance. While these changes in luminance may correspond in general either to material changes in surface property or to illumination effects, the mechanisms used by the visual system to disambiguate the two in the achromatic domain are as yet poorly understood. Specifically, how does the visual system distinguish between two contours which cross at a junction, when one contour is due to a material change and the other to a change in illumination?

Figure 1a shows a classical zero-disparity illusory-transparency stimulus consisting of a bicoloured background overlaid with a rectangular filter. The phenomenal segmentation of the homogeneous filter layer from the bipartite background is effortless and quite compelling. Kanizsa (1979) referred to three types of conditions for the occurrence of this type of transparency: chromatic, topological, and figural. Collapsing the latter two, the conditions necessary for the perception of transparency can be broadly separated into intensity and figural parameters. Intensity conditions describe the luminance (or contrast) and chromatic relationships between parts of a putative transparent surface and its background. Most of the research in transparency has been devoted to the development of models which describe and predict the achromatic luminance and contrast relationships required to give rise to perceptual transparency (eg Metelli 1970;



(a) (b)

Figure 1. (a) Classical bipartite background overlaid with a transparent filter, and inset (b) X junctions defined.

Beck et al 1984; Metelli et al 1985; Gerbino et al 1990; Masin 1991, 1997; Gerbino 1994; Singh and Anderson 2000; Westland and Ripamonti 2000; Kasrai and Kingdom 2001).

Figural conditions, on the other hand, determine the arrangement and orientation of contours which separate different parts of the image. As an illustrative example, take the two images adapted from Kanizsa (1979) in figure 2, which demonstrate a disparity in percept strength due to different figural arrangements. Even though both images contain contours which cross (one caused by a change in background reflectance and the other by an illusory filter), the relative orientation of the contours is not identical. While comparative empirical analyses of different intensity models have already been reported (Gerbino et al 1990; Kasrai and Kingdom 2001), a quantitative survey of the role of figural conditions remains incomplete. In this paper the figural conditions necessary for single-plane achromatic transparency will be examined with a novel technique which has been successfully utilised to study intensity conditions.

(a) (b)

Figure 2. Discontinuity in direction of (a) the filter contour versus (b) the background (reflectance) contour.

1.1 *Formal classification of junctions*

To establish a common nomenclature, a brief overview of junction classification is presented (see also Todorović 1997). Junctions can be formally labelled as '3 junctions' or '4 junctions', depending on the number of contours which come together at the junction. Junctions of the type normally encountered in the transparency stimuli depicted in figure 1a will be 4 junctions, as shown in the inset (figure 1b). If the 4 junction consists of two pairs of collinear (but not necessarily perpendicular) contours, it is called an X junction, whereas if only two of the four contours are collinear, it is referred to as a Ψ junction (see figure 7b). Similarly, 3 junctions consisting of two collinear contours are called T junctions. In the context of these definitions, it has been suggested that T junctions serve as a cue for occlusion of one surface by another (see figure 3d), but that X junctions trigger transparency perception.[1] But it is not true that all X junctions automatically lead to perceptually valid transparency.

1.2 *Intensity conditions*

Although we focus in this paper on the role of junctions, it is necessary to consider the intensity relationships required for achromatic transparency in order to understand the particular techniques employed here to study figural conditions. Metelli (1974) proposed the first quantitative model describing the reflectance relationships required for phenomenal transparency. Although others have since suggested alternative models which use contrast (Singh and Anderson, in press) or lightness (Beck et al 1984) instead of physical reflectance, a more general model based on luminance, called the luminance episcotister (LE) model (Gerbino 1994), is used here. The performance of human observers with stimuli containing illusory transparency has already been compared with the LE model and other models (Beck et al 1984; Gerbino et al 1990; Singh and Anderson, in press; Kasrai and Kingdom 2001). We showed, using a new technique described in section 1.4, that subjects' adjustments were not only very precise, but also very accurate when compared to the LE model (Kasrai and Kingdom 2001).

Given how well it predicts human observers' responses to stimuli containing simulated transparency, the LE model (described below) was chosen as the intensity model for the stimuli generated in this study. Taking a stimulus with a simple bipartite background and an overlying transparent filter (such as figure 1a), the luminances of the transparent regions P and Q are

$$P = tA + F\,, \quad \text{and similarly} \quad Q = tB + F\,, \tag{1}$$

where t is the transmittance of the filter, A, B, P, and Q are the luminances of the two background and two layer regions, respectively, and F is the additive term due to the reflectance of the filter. The implication here is that the absolute value for the reflectance of the filter is inseparable from the illumination component of the filter, which in the general case is not necessarily the same as that of the background.

1.2.1 *Contour polarity and ordinal rules.* Just as algebraic models attempt to provide a fine-scale description of the optimal intensity relationships for transparency, ordinal rules governing the correct arrangement of intensities around the junction predict in a coarse fashion whether a stimulus contains a plausible or implausible transparent medium. These qualitative rules have been shown to give rise to consistent predictions regardless of the exact algebraic model used (compare, for example, Kersten 1991, page 213; Anderson 1997, page 424; Beck and Ivry 1988, page 588).

A *polarity*, or relative direction, can be assigned to a contour depending on its flanking luminances, eg positive polarity if the region on the right is brighter than the one on the left. If the brightness order is reversed as the contour crosses through an X junction, the contour is said to reverse polarity (see figure 3b). If both pairs of contours in the X junction reverse polarity, it is called a double-reversing junction (see figure 3c). Non-reversing X junctions (see figure 3a) result in bistable transparency percepts, where the depth order of the two surfaces is ambiguous; single-reversing junctions (figure 3b) give rise to transparency with a unique depth order; and double-reversing X junctions do not evoke a transparent percept. Beck and Ivry (1988) alluded to the same luminance-order constraints by suggesting that "the likelihood of perceptual transparency is increased when the direction of lightness changes across an x-junction is in the same direction" (page 589) or, in the words of Adelson and Anandan (1990, page 80), "an edge which is transparently occluded cannot reverse sign, while an edge which is in front

[1] At least two studies have shown empirically that under specific stimulus conditions, where the X junctions are implied from T junctions, the perception of transparency can be just as compelling (Watanabe and Cavanagh 1993; Anderson 1997).

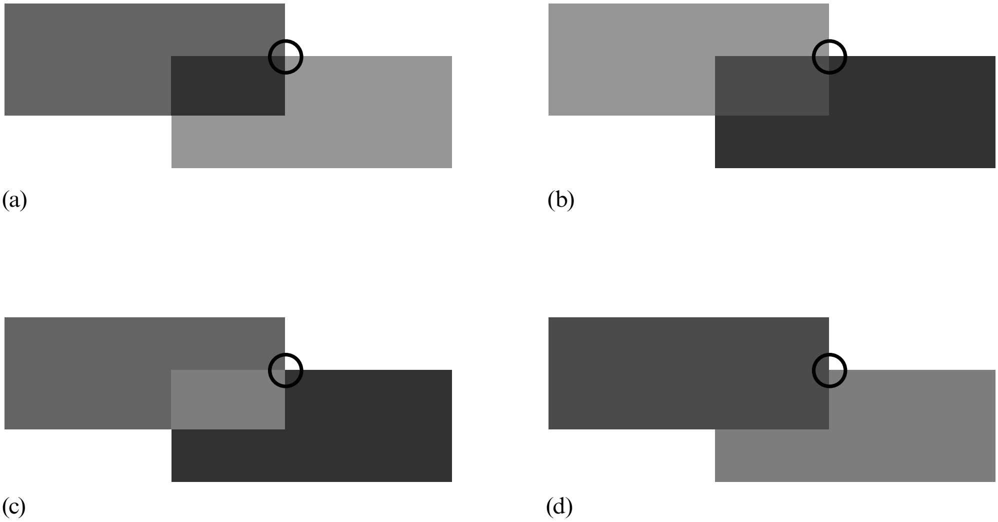


Figure 3. Examples of (a) non-reversing, (b) single-reversing, and (c) double-reversing X junctions; also, (d) a T junction.

may or may not reverse sign". Within the context of these broad qualitative rules, algebraic models simply place additional constraints on the solution space of perceptually valid transparent stimuli. In the experiments described in this paper we analysed the data in terms of both the coarse ordinal as well as the fine algebraic constraints in order to observe the effect of changes in figural conditions on the processing of transparency by the visual system.

1.3 *Figural conditions*

Metelli (1974, page 92) outlined three figural conditions which follow from Gestalt principles: "figural unity of the transparent layer, continuity of the boundary line and adequate stratification". These conditions describe generally that the layer must: appear as a whole, segmentable surface; not have any abrupt changes in the continuity of its boundary; and appear to be between the observer and the background, such that "the underlying regions must appear to meet under the whole of the transparent layer". Kanizsa (1979, page 158) also demonstrated that "each one of the two areas to be unified in the transparent surface [eg P and Q in figure 1a] must be in contact with the homologous area [eg A and B, respectively] and with only one of the two other areas". Taken together, these define qualitative constraints on the nature of contours and junctions (see section 1.1) which normally occur as a result of cast shadows, transparent media, or changes in material. Binocular X junctions also occur in stimuli containing stereo disparity; however, a discussion of multiplane (stereoscopic) transparency is beyond the scope of this study.

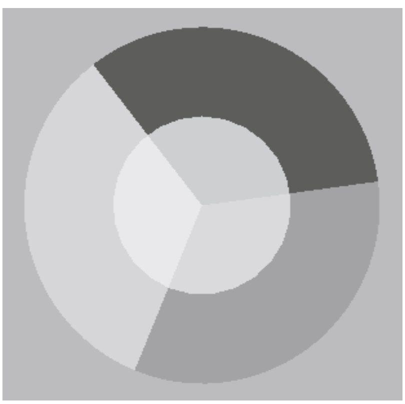
That the existence of X junctions is not a sufficient condition for perceptual transparency can easily be shown by observing figure 1b. The mere presence of an X junction with four surrounding luminances does not result in a strong segmentation into layer and background without the added context of the rest of the figure. The questions that remain are whether X junctions constitute a *necessary* condition for phenomenal transparency, and which characteristics of X junctions change the saliency of a transparent percept. Adelson (1993) has demonstrated a variant of the argyle illusion where two identical patches, one inside and one outside an illusory transparent strip, were shown to have a 70% difference in luminance. But when the X junctions defining the illusory transparency were destroyed, the effect was found to be reduced to 20%. He concluded that "the sense of transparency tends to be reinforced by the X junctions" (page 2044).

Overall, very few studies have endeavoured to quantify the specific role of junctions in phenomenal transparency. In this study, three stimuli were employed as figural manipulations to examine how destruction or perturbation of X junctions affects the strength of a transparent percept, as measured by subjects' settings compared with the LE model.

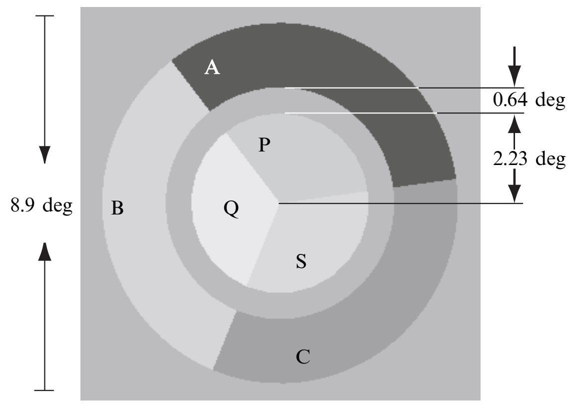
1.4 *Six-luminance stimulus*

For this purpose a six-luminance stimulus described previously (Kasrai and Kingdom 2001) was employed as shown in figure 4. Six luminances are the minimum number required in a transparency stimulus to interrogate the visual system's internal model. Although four luminances (see for example figure 1) are the minimum number required to obtain a transparent percept, fixing three of the luminances (eg *A*, *B*, and *P*) and manipulating the fourth luminance (*Q*) simply varies the reflectance or transmittance of the simulated filter (Singh and Anderson 2000).[2] On the other hand, in a six-luminance display, such as that in figure 4, holding constant four of the luminances (two background and two foreground—*A*, *B*, *P*, and *Q*, respectively) fixes the transmittance and reflectance of the filter, whatever they may be in a particular subject's internal representation, while the fifth luminance (*C*) serves as a test background patch. The subject then adjusts the sixth luminance (*S*), which makes up one-third of the filter, to 'complete' the filter. It is worth noting that the geometry of the stimulus in its 'neutral' (concentric disks) configuration satisfies the conditions described by Metelli and Kanizsa (see 1.3 above) in that the third (test) sector completes the inner transparent disk, and the reflectance contours of the background meet under the layer. As will be shown later, the six-luminance stimulus can also be easily modified to measure the efficacy of other figural conditions.

The qualitative effect of contour polarities on the six-luminance stimulus can be observed in figure 5. The figure shows a range of six-luminance stimuli with the variable test patch gradually changing from dark to light (from top-left to bottom-right). According to the LE model, the image in the middle of the second row corresponds to the optimal transparent stimulus. The polarity of the contours is marked by arrows (pointing from darker to lighter) in three cases. Of these three exemplar stimuli it is



(a)



(b)

Figure 4. Circular six-luminance stimulus (a), and circular stimulus with occluding annulus and figural details (b).

[2] The three-luminance stimulus described by Fuchs (1923) which gives rise to a transparent percept under specific conditions is not considered here.

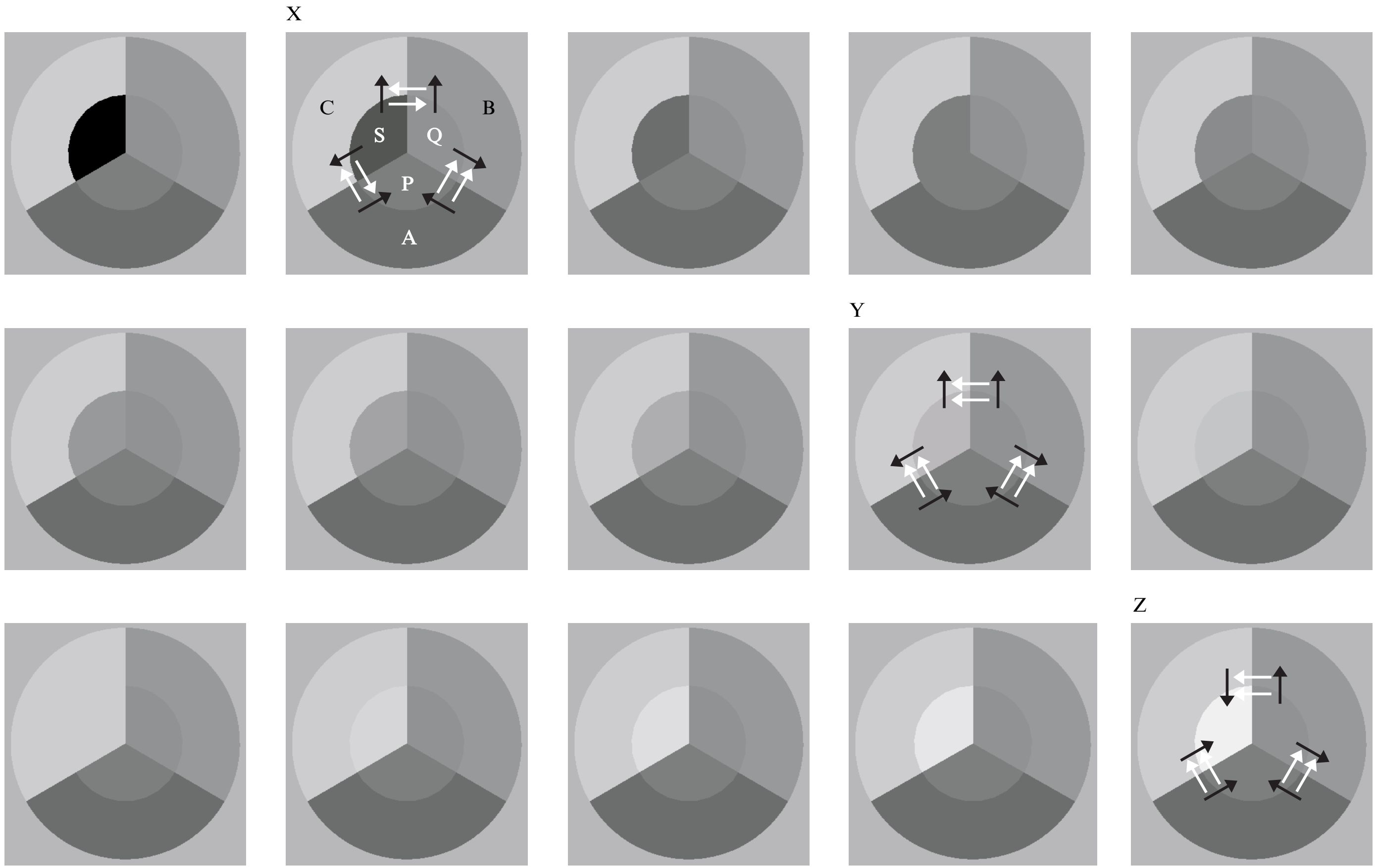


Figure 5. Example range of possible test-patch settings. The image containing the correct luminance combination as predicted by the LE model is in the centre. Images labelled X, Y, and Z are sample stimuli, annotated with arrows illustrating contour polarities. White arrows indicate the polarity of reflectance edges while black arrows show the polarity of the filter's contours.

only image X, in which the reflectance edges (white arrows in the angular direction) change polarity, that gives rise to a strictly nontransparent percept. In the cases of Y and Z the reflectance edges consistently have non-reversing polarity (note parallel white arrows). For the purposes of this paper, stimuli similar to case X will hereafter be called polarity-reversing stimuli, referring strictly to the ordinal property of the reflectance edge.

As for the edge corresponding to the transparent filter, in this case the circular contour defined by the inner disk, recall that according to the contour polarity rules it may or may not change sign (note the parallel and antiparallel black arrows). Also, when neither of the two intersecting contours reverses polarity, as in some of the junctions in stimuli Y and Z (just as in figure 3a), the *local* depth-order information is metastable at the junction. Because of the unity of the figure, however, the depth-order ambiguity is resolved by the other single-reversing junction(s) in the stimulus.

In addition to the benefits derived from integrating the reference and test areas into a single display [as opposed to having two side-by-side four-luminance images as Gerbino et al (1990) did], the six-luminance stimulus affords certain advantages regarding stimulus geometry. The stimulus contours can be easily manipulated to simulate different figural conditions, including those demonstrated in figure 2. A brief report of some of these findings has been presented previously (Kasrai and Kingdom 2000).

2 General methods

2.1 *Stimulus generation*

Although the figural arrangement of the stimuli changed from experiment to experiment, all the stimuli used in these studies were composed of six luminances — three background and three layer luminances (see figure 4b). The three background luminances (A, B, C) were chosen randomly, along with random values for the transmittance t (between 0.2 and 0.8) and reflective component ($F \geqslant 0$) of the filter, such that the maximum luminance of the monitor ($\simeq$33 cd m^{-2}) was not exceeded. An additional constraint ensured that no two adjacent patches had similar luminances (ie were within 2 cd m^{-2} of each other). Two of the three layer luminances (P and Q) were calculated according to the LE model [see equation (1)]. The third layer luminance (S) was the variable test patch. The luminance of the area surrounding the stimulus was fixed at an intensity of half the maximum luminance produced by the display (ie $\simeq$17 cd m^{-2}). Image pairs were viewed binocularly through a custom-built eight-mirror stereoscope with a principal-ray path length of 45 cm and a maximum aperture of 9.5 cm $\times$ 9.5 cm, for a maximum visual angle of 7.1 deg. Even though all parts of the image were in the plane of fixation, a stereoscope was used because these experiments were part of a larger project in which some stimuli were presented dichoptically or stereoscopically.

2.2 *Display*

All experiments were performed with an SGI (Silicon Graphics, Inc, Mountain View, CA, USA) O2 workstation (150 MHz R10000 processor) on a 17-inch monitor displaying 1280 pixels $\times$ 1024 pixels at a vertical refresh rate of 72 Hz. The luminance output of the monitor was measured by using a single-channel optometer with photometric detector (United Detector Technology Model S370, Hawthorn, CA, USA), and calibrated to produce the desired luminances between 0 and 33 cd m^{-2}.

2.3 *Subjects*

The subjects consisted of seven experienced psychophysical observers (RK, FK, PP, KW, CR, HW, and NP) with normal or corrected-to-normal vision. Apart from the two authors, the subjects were kept naïve as to the purposes of the study.

2.4 *Procedure*

2.4.1 *Method of adjustment.* Two different procedures were employed in each of the following three experiments. The first procedure, the method of adjustment, consisted of subjects manually varying the luminance of test patch S, using the computer mouse to drag a slider on the display, such that they perceived the transparent layer as a contiguous filter with uniform transmissive and reflective characteristics on the tripartite background. In experiment 1 (see section 3) each block contained both experimental and control conditions which were randomly intermixed, resulting in 60 adjustments in each condition. In experiments 2 and 3, each subject made 120 settings over three sessions of 40 trials. The luminance S was set to a random value at the beginning of each trial. Figure 5 illustrates the range of possible settings of the test patch S, from 'black' to 'white', for a fixed set of the parameters A, B, C, t, and F. The subjects' settings of S for such stimuli were converted to residuals by subtracting the value predicted by the LE model described in equation (1):

$$S_{\text{predicted}} = tC + F,$$
$$\text{residual} = S_{\text{predicted}} - S_{\text{experimental}}\,. \qquad (2)$$

The root-mean-square (rms) of the residuals for each condition were taken as a measure of the subject's accuracy in processing transparency.

2.4.2 *Two-alternative forced-choice.* As a result of the unlimited stimulus presentation time in the adjustment task, subjects may have developed cognitive strategies which aided them in making adjustments. Therefore, a second technique with a short presentation time was also used in order to minimise the possibility of such putative computational strategies. A two-alternative forced-choice (2AFC) technique was employed whereby each subject performed a total of 720 trials (360 trials for each of the experimental and control conditions) in blocks of 120 trials. The stimulus presentation time was 250 ms (Masin 1998), with a 500 ms interstimulus interval. A small black fixation point was added in the centre of the disk. For the 'correct' stimulus of each forced-choice pair, the test luminance S was set according to the LE model [see equation (1)]. For the 'incorrect' stimulus, this model luminance S was multiplied by a factor chosen at random from the following list: 0.5, 0.7, 0.9, 1.1, 1.3, 1.5. Since both this factor and the model parameters (A, B, C, t, and F) were generated randomly, it was ensured that the expected (ie correct) luminance S fell between P and Q so that polarity reversals (such as in stimulus X in figure 5) would occur in about half the trials. Clearly one would expect performance measured by the proportion-correct responses to be, in general, worse for multiplication factors close to 1.0, which result in similar test patch luminances (S) in both presentations, not only because subjects would not be able to discriminate as well between two very similar stimuli, but also because such small increments or decrements are unlikely to have changed the ordinal characteristics of the X junction. The subjects' task was to select the stimulus with 'best transparency', similarly to in the adjustment task. Audio feedback was provided for incorrect responses.

3 Experiment 1: Occlusion of the junction

In the first experiment we aimed to assess the result of eliminating or occluding X junctions. We used an annulus which was fixed at the mid-grey surround colour and which straddled the contour of the simulated filter. Figures 4a and 4b, respectively, show the circular stimulus without and with the occluding annulus. Figure 4b describes in detail the configuration of this stimulus.

For the adjustment task, the rms residuals as calculated from equation (2) are shown in the first column-pair of table 1. Lower rms scores generally indicate better performance. Even though not every subject's results reach significance on an individual basis,

Table 1. Root-mean-square (rms) residuals (cd m^{-2}) for all subjects. The second-to-last row shows the rms error for each condition, averaged across subjects. The standard error, based on repeated measures, is marked in parentheses next to each value. The last row shows the two-way ANOVA results.

Subject	Annulus	(control)	Kink	(control)	Clover	(control)
RK	2.94 (0.34)	2.61 (0.29)	2.40 (0.30)	2.16 (0.28)	2.69 (0.33)	2.48 (0.31)
FK	4.83 (0.48)	2.95 (0.30)	4.09 (0.40)	3.89 (0.45)	4.86 (0.49)	3.10 (0.34)
PP	2.75 (0.34)	2.90 (0.36)	2.76 (0.32)	3.35 (0.39)	2.93 (0.41)	3.39 (0.46)
KW	2.82 (0.42)	2.65 (0.33)	2.38 (0.29)	2.93 (0.37)	2.85 (0.33)	2.51 (0.30)
CR	3.91 (0.55)	3.31 (0.38)	3.35 (0.42)	3.85 (0.47)	4.06 (0.46)	4.10 (0.46)
NP	3.44 (0.44)	2.54 (0.36)	2.24 (0.31)	3.07 (0.37)	3.22 (0.52)	2.58 (0.28)
HW	3.08 (0.35)	2.86 (0.33)	2.88 (0.38)	2.95 (0.34)	3.29 (0.42)	2.82 (0.36)
Mean	3.40	2.83	2.87	3.17	3.42	3.00
p	< 0.01		0.03		< 0.01	

there is a main effect of annulus ($F_{1,826} = 9.25$, $p < 0.01$) showing better performance overall (lower rms) in the non-occluded stimuli.

Turning now to the forced-choice results, for each subject, data from stimuli which had been perturbed from the LE model to produce contour polarities which do not induce transparency (as in case X in figure 5) were grouped together a posteriori, regardless of the random perturbation factor. These were separated from those trials where the ordinal properties were consistent with unique transparency (as in Y and Z in figure 5; see also figure 3b). Table 2 shows the 2AFC proportion-correct scores for all subjects. The results (first two column-pairs) thus show four proportion-correct scores

Table 2. Proportion-correct scores for all subjects. Each column-pair contains the score for the experimental condition ('exp', on the left side) followed by the score for the corresponding control condition ('con', right side). The respective binary errors (BE) are shown below each score. The second-to-last row shows for each condition the average score across all subjects, and the last row shows the p values resulting from the ensemble binary tests for significance between experimental and control conditions.

Subject	Annulus				Kink				Clover			
	reversal		no reversal		reversal		no reversal		reversal		no reversal	
	exp	con	exp	con	exp	con	exp	con	exp	con	exp	con
RK	0.80	0.97	0.71	0.67	0.93	0.95	0.68	0.69	0.91	0.98	0.66	0.65
(BE)	0.03	0.01	0.03	0.04	0.02	0.02	0.04	0.04	0.02	0.01	0.04	0.04
FK	0.80	0.86	0.55	0.70	0.81	0.84	0.65	0.62	0.57	0.76	0.55	0.63
(BE)	0.03	0.03	0.04	0.04	0.03	0.03	0.04	0.04	0.04	0.03	0.04	0.03
PP	0.66	0.83	0.56	0.60	0.78	0.71	0.68	0.64	0.85	0.78	0.59	0.61
(BE)	0.04	0.03	0.04	0.04	0.03	0.03	0.04	0.04	0.03	0.03	0.04	0.04
KW	0.89	0.89	0.60	0.60	0.96	0.92	0.64	0.68	0.93	0.95	0.66	0.63
(BE)	0.02	0.02	0.04	0.04	0.01	0.02	0.04	0.04	0.02	0.02	0.04	0.04
CR	0.66	0.84	0.57	0.62	0.82	0.91	0.64	0.69	0.79	0.93	0.62	0.66
(BE)	0.03	0.03	0.04	0.04	0.03	0.02	0.04	0.03	0.03	0.02	0.04	0.04
NP	0.56	0.89	0.58	0.68	0.78	0.88	0.67	0.68	0.91	0.88	0.59	0.60
(BE)	0.04	0.02	0.04	0.04	0.03	0.02	0.03	0.04	0.02	0.02	0.04	0.04
HW	0.72	0.79	0.60	0.65	0.80	0.86	0.68	0.56	0.77	0.78	0.56	0.66
(BE)	0.03	0.03	0.04	0.04	0.03	0.03	0.03	0.04	0.03	0.03	0.04	0.04
Mean	0.73	0.87	0.60	0.65	0.84	0.87	0.66	0.65	0.82	0.87	0.60	0.63
(BE)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
p	$\ll 0.001$		< 0.01		0.03		0.31		$\ll 0.001$		0.06	

for each subject: (with annulus versus without annulus) × (polarity reversing versus not polarity reversing). These individual proportion-correct scores were pooled and averaged, and a binomial test of significance (Bain and Engelhart 1991) was performed. Both the polarity-reversal ($p \ll 0.001$) and no-polarity-reversal ($p < 0.01$) conditions showed a significant difference between the annulus and no-annulus conditions.

These results, together with the rms values from the adjustment data show that the simple occluding annulus shown in the stimuli in figure 4 slightly, but significantly, reduces or degrades the ability to process transparency accurately.

It must be pointed out that the occluding annulus did not change the alignment of the contours which make up the X junction, and was in fact concentric with the original layer – background and background – surround contours. An argument may thus be made that although the *local* X junction had been destroyed in experiment 1, according to the classical definition of X junctions (see section 1.3) the visual system may easily interpolate between the two pairs of collinear contours into a (non-illusory) X junction.[3] Nonetheless the destruction of the local X junction resulted in a sufficient disruption of the transparent percept to reduce performance on average in both adjustment and 2AFC tasks.

In order to ensure that the performance differences observed in the presence of the annulus were due only to the occlusion of the X junctions and not to the particular unified shape of the annulus, an additional control experiment was performed with a different stimulus, shown in figure 6. Mid-grey disks with diameters equal to the width of the annulus (see figure 4b) were superimposed on the original six-luminance stimulus to occlude the three X junctions locally. Only the 2AFC technique was used with the participation of four (RK, FK, NP, and KW) of the seven subjects. They performed 720 trials each over 12 blocks; the luminances in the stimuli were calculated as above and the two conditions (grey patches versus no occlusion) were interleaved randomly within the blocks.

Figure 6. Stimulus for local junction-occlusion control experiment. Mid-grey disks are used to occlude the X junctions.

The data, analysed as above with a binomial test, reveal a significant difference in performance for the stimuli containing polarity reversals ($p < 0.001$), but no difference for the no-polarity-reversal stimuli ($p = 0.19$). Along with the results of the previous annulus experiment, we can conclude from the trends in this experiment that the occlusion of X junctions does indeed hinder subjects' ability to encode transparency, be the occlusion limited locally or part of a global stimulus structure.

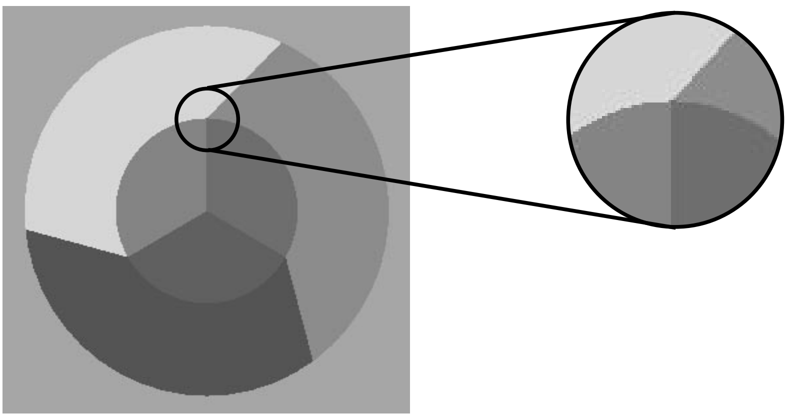
[3] Indeed, the observers in this study did not report perceiving illusory contour completions across the annulus.

4 Experiment 2: Discontinuity of the background contour

In the next two experiments the significance of the alignment of the four contours was examined. Kanizsa's two examples (1979; see also figure 2) showed stimuli where the alignment of the contours was not preserved. In other words, either the contours corresponding to the transparency edge (filter – background), or the ones corresponding to the reflectance edge (separating the two background colours) have an undefined gradient at the Ψ junction. Even though Kanizsa was not explicit in his categorisation of these two different conditions, he claimed in the former case that the figural conditions were "not favorable to the impression of transparency", whereas for the latter case he states that "continuity of direction is not a necessary condition of phenomenal transparency" (page 161).

Two variants of the original circular six-luminance stimulus were used to examine the two cases separately (in this experiment and the next), each with its own control condition.

The stimulus, shown in figure 7, was the same as the original six-luminance stimulus, except that the reflectance contours of the background were kinked (or tilted) by 45°. In addition to the 120 adjustments on this stimulus, the subjects also made another series of adjustments on a control stimulus with 0° kink in the background contours. Even though this control stimulus is identical to the no-annulus stimulus of experiment 1 (figure 4a), these data were collected contiguously along with the 45° kink condition because of the time lag in data collection between experiments 1 and 2. Note that whereas in experiment 1 the experimental and control stimuli were interleaved randomly within the adjustment and 2AFC blocks, in experiments 2 and 3 it was the experimental blocks which were presented in quasi-random order.



(a) (b)

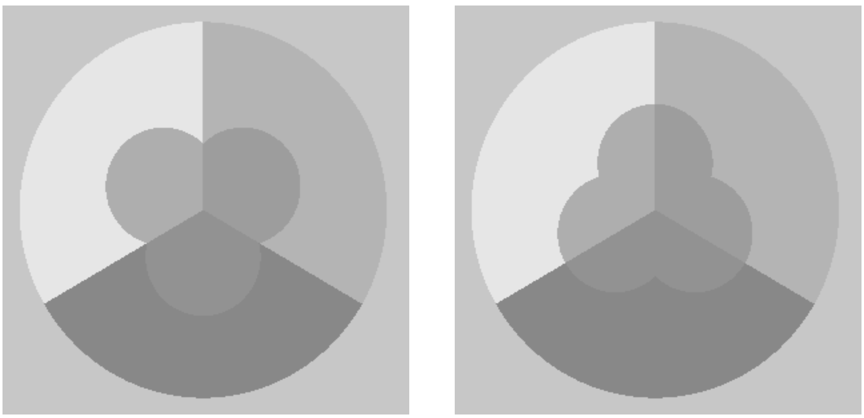
Figure 7. (a) Stimulus for experiment 2 with 45° kink, and inset (b) showing Ψ junction.

The residuals from the adjustment data were again compared to the expected settings derived from the LE model. The subjects' results, similarly to experiment 1, show no consistent *individual* differences between the kink and the no-kink conditions. However, the pooled two-way ANOVA results show a significant effect of kink angle ($F_{1,1666} = 4.51$, $p = 0.03$) but, as shown by the subject means in tables 1 and 2, this time with *better* performance in the kink condition.

The binomial test also revealed a significant overall difference in the pooled and averaged 2AFC proportion-correct data in the polarity-reversal condition ($p = 0.03$) but not in the no-polarity-reversal condition ($p = 0.31$). As with the adjustment results above, the subjects' overall performance was *better* (lower rms, and higher proportion-correct scores) with the experimental stimulus (45° kink) than with the control stimulus (no kink).

5 Experiment 3: Discontinuity of the layer contour

In this experiment we destroyed the *continuity* of the filter – background contour. For this, we used a clover-leaf pattern for the simulated transparent layer. The geometry of the layer consisted of three overlapping circles, each with a 1.4 deg radius, with centres about 2.2 deg away from the stimulus centre, producing a three-leaf clover pattern. In the experimental condition, the orientation of the clover pattern with respect to the tripartite background was such that a so-called minimum of curvature occurred at the Ψ junction, as shown in figure 8a. In the control condition the clover pattern was rotated 60° with respect to the background, restoring the continuity of the filter boundary at the junction, as in figure 8b. The latter served as a natural control stimulus because apart from the contour geometry of the junction the individual sector areas and overall shape of the filter remained constant. Thus, any performance differences cannot be due to the shape or area of the overlay.



(a) (b)

Figure 8. (a) Clover stimulus for experiment 3, and (b) rotated clover stimulus as control condition.

In both the adjustment and 2AFC experiments, subjects' overall performance was worse in the experimental condition compared with the control. A two-factor (subjects × clover orientation) ANOVA of the adjustment data shows an effect of the orientation of the transparency overlay ($F_{1,1666} = 8.69$, $p < 0.01$).[(4)] For the 2AFC data, the binomial test shows a significant difference only in the polarity-reversal data sets ($p \ll 0.001$), and not in the no-polarity-reversal data sets ($p = 0.06$).

6 Summary and general discussion

For ease of analysis, the averaged results have been replotted in figures 9 and 10. The plots show respectively the rms residuals for all adjustment conditions and percent-correct scores for all 2AFC conditions, averaged across all subjects. The results of the statistical analyses (see the bottom rows in tables 1 and 2) generally correspond to what can be gleaned from the phenomenal experience associated with the stimuli, namely that under certain figural conditions the degradation of the transparency percept is matched by a reduction in the accuracy with which subjects process transparency. Performance is on average worse in relation to the LE model [see equation (1)] in the stimuli where the X junction is occluded (experiment 1) or where an extremum of

[(4)] It should be noted that in this experiment, as in the previous two, there was also a significant effect of differences between the subjects ($p \ll 0.01$). In addition, there were also effects of interaction between subjects (rows) and experimental condition (columns) in this experiment ($F_{6,1666} = 4.21$, $p < 0.001$) as well as in experiment 1 ($F_{6,826} = 2.26$, $p = 0.04$). These effects are neither particularly surprising nor as interesting as the differences due to the changes in the stimulus condition.

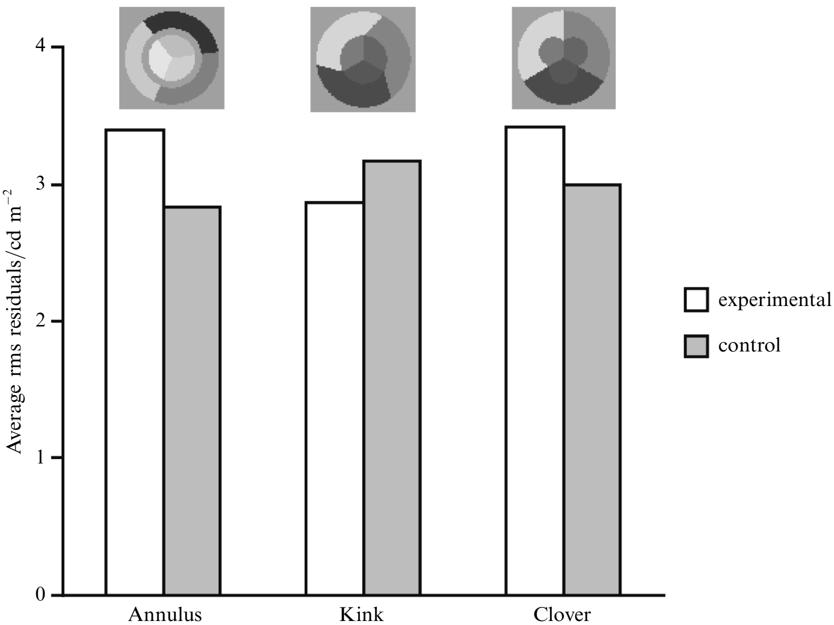


Figure 9. Adjustment data for all three experiments averaged across all subjects. See table 1 for details.

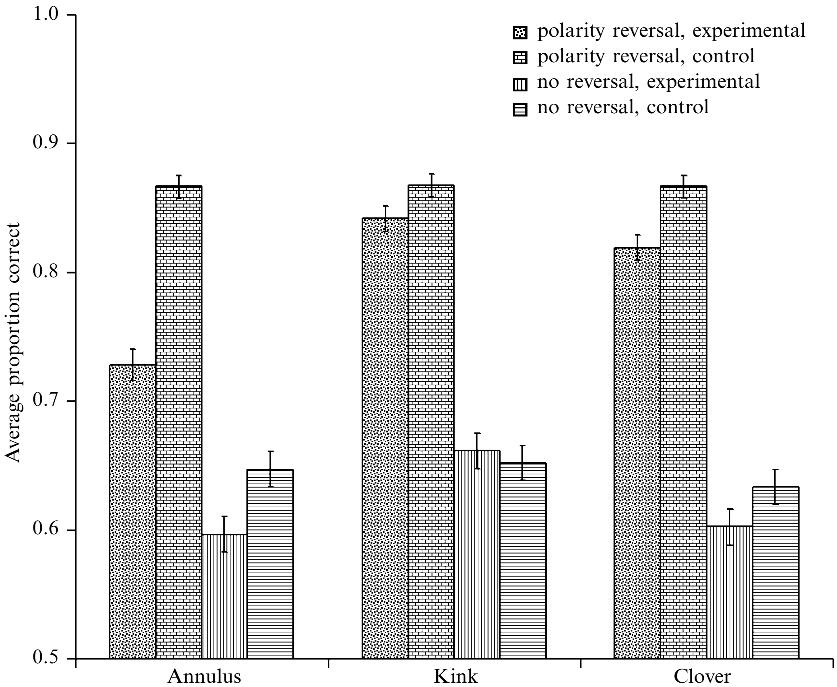


Figure 10. 2AFC data for all three experiments averaged across all subjects. Error bars are similarly subject-averaged binary errors (BE). See table 2 for details.

curvature of the layer – background contour exists at the Ψ junction (experiment 3). Conversely, a discontinuity in the direction of the contours which define a reflectance boundary (the background) at the Ψ junction does not degrade performance (experiment 2) but slightly improves it. These quantitative results are in agreement with Kanizsa's qualitative arguments demonstrated by the images in figure 2.

Singh and Hoffman (1998) have discussed in detail the case where the contour of the transparent filter (but not that of the background) has a direction discontinuity at the junction. They manipulated the sign of curvature, turning angle, and level of smoothing of the filter contour, and asked subjects to judge the change in the salience of perceptual transparency by rating on a 7-point scale the strength of a four-luminance transparency stimulus. They found that it was sufficient for the filter contour to have a strong maximum or minimum of curvature at the junction in order to have a loss of phenomenal transparency. In the study reported here, rather than rating the subjective saliency of the transparency, the subjects' *accuracy* in processing simulated transparency was measured. In addition, not only was the influence of the contour of the filter examined here, but also that of the reflectance contour. The results of the clover experiment (experiment 3) are consistent with Singh and Hoffman's (1998) results insofar as the salience of the clover pattern as a transparent overlay was reduced compared with the condition with continuous contours through the junction.

6.1 *Adjustment results*

The results of the statistical analyses require a caveat, however. If the rms results are reanalysed in a leave-one-out fashion whereby the data from one of the five subjects are omitted in turn, the relative weight or influence of each subject's results can be determined. In the occluding-annulus condition (experiment 1), leaving out CR or RK's results does not change the ANOVA results ($p \simeq 0.01$). Leaving out FK's data, on the other hand, raises the p value to 0.11, indicating that the large difference between FK's annulus and no-annulus conditions single-handedly pushes the ensemble results into being statistically significant. Similarly, in the clover condition (experiment 3), the p value increases from $p < 0.01$ to $p = 0.31$ when FK's data are omitted. In the light of this one may say that the effect using the method of adjustment is subject to large interobserver variability.

6.2 *Two-alternative forced-choice results*

The 2AFC results are generally more consistent than the adjustment data, showing larger differences between experimental conditions (compare RK and CR's 2AFC polarity-reversal data in all three conditions). A cursory inspection of the 2AFC data reveals that, even when subjects' results do not reach significance on an individual basis, the differences between the control and experiment data (in the annulus and clover experiments) across all subjects are generally in the same direction. Consequently the same leave-one-out examination of the results as in the adjustment data above was not performed. The differences between the adjustment and 2AFC results appear to confirm our apprehension regarding the use of cognitive strategies in the adjustment task. Since subjects had unlimited time to complete each adjustment, and there was no audio feedback possible for training purposes, it is difficult to know unequivocally the basis of their adjustment stratagem.

An additional set of analyses can be performed on the 2AFC results regarding the ordinal rules for '4 junctions' (see section 1.2.1). With reference to table 2, the effects of changes in contour polarity which are inconsistent with transparency perception can be seen by comparing each polarity-reversal column-pair with its corresponding no-polarity-reversal column-pair for the same condition. For example, considering the row of mean percent-correct scores (the second-last row of cells) in the clover condition (experiment 3), the scores for the polarity-reversing stimuli are dramatically reduced from 0.82 and 0.87 to 0.60 and 0.63. A binary test of the data for all three experiments showed a highly significant ($p \ll 0.001$) superiority in performance in the polarity-reversal cases compared to the ones with no polarity reversals, confirming what can be observed by visual inspection. Subjects thus performed on average worse on trials in which both stimuli had contour polarities consistent with a transparent filter, compared with trials which contained an 'incorrect' stimulus with reversals in the polarity of the background contour. This indicates that the polarity of 4 junctions is an extremely salient feature which is used to distinguish plausible from implausible transparent media, as hypothesised.

6.3 *Possible explanations*
On the basis of these results it is possible to speculate as to the mechanisms underlying the perception of achromatic transparency. As mentioned in the introduction, transparencies and shadows can be more generally thought of as bringing about changes in illumination. It is conceivable, as Adelson and Somers (2001) have suggested, that the visual system considers jagged edges as more likely to be reflectance edges than illumination ones. Reflectance changes in an image define not only textures on surfaces, but also material changes between *different* surfaces, be they two surfaces in different depth planes or adjacent to one another. On the other hand, illumination contours are usually due to shading, changes in lighting level, or transparent filters. These latter contours are more likely to be either smoothly varying or blurred, or, when sharp, due to straight edges of objects which somehow occlude the illuminant. In other words, whereas reflectance contours are generally non-differentiable (ie have an undefined gradient) along the direction of the contour, illumination edges are more likely to be straight or smoothly varying.

This hypothesis may also serve to explain why there was a slight improvement of performance in the 45° kink condition compared with the control condition. Although in theory sudden kinks in the background (reflectance) contours are not inconsistent with transparency, it may be the case here that the control condition (0° kink) created a weak three-dimensional effect which was destroyed in the experimental condition. Even though there was no disparity in the images, some subjects reported perceiving the centre of the disk as the corner of a room or a cube. This interpretation was less likely in the experimental condition, and this may have aided the subjects' performance.

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