Achromatic transparency

Walter Gerbino
University of Trieste, Trieste, Italy
Department of Life Sciences and B.R.A.I.N. Center for Neuroscience

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1. History and definitions

Phenomenal transparency is a key property of perceptual organization, emerging under appropriate stimulus conditions and often coupled with other aspects of experienced wholes. In the framework of percept-percept coupling (Epstein 1982; Hochberg 1974; Savardi and Bianchi 2012), transparency may be both an effect and a cause, as evidenced in the title of a seminal paper by Kanizsa (1955) and argued by Nakayama et al. (1990).

Broadly speaking, transparency is a good label for any instance of experiencing something *through* something else. In vision, we can see an object – sometimes vividly, sometimes vaguely – through a piece of glass, a medium like smoke or an image reflected on the surface of a pond; a double experience that intrigued vision theorists (Arnheim 1974, p. 253; Gibson 1975, 1979; Koffka 1935, pp. 260-264), painters like Paul Klee (1961; Rosenthal 1993), designers and architects (Kepes 1944; Rowe and Slutzky 1963), and plays a crucial role in visualization techniques (Chuang et al. 2009; Stone and Bartram 2008). In audition, Bregman (1996, 2008; Denham and Winkler, Chapter 39, this volume) emphasized that perceiving sounds through other sounds is ordinary in auditory scene analysis. In touch, transparency has been analyzed by Katz (1925/1989; Krueger 1982) and constitutes a relevant aspect of product design and experience (Sonneveld and Schifferstein 2008, p. 60). [1]

In the present chapter transparency qualifies the phenomenal possibility of seeing something through something else and shifting attention from what is in front to what is behind, along the same line of sight. With respect to perceptual organization, transparency supports the modal completion of partially occluded contours, while occlusion requires their amodal completion (Van Lier and Gerbino, Chapter 11, this volume). To a first approximation, the physical counterpart of phenomenal transparency is transmittance; i.e., the fraction of light that a layer allows to pass through without modifying its structure.

The chapter is focused on vision in a grey world. Independently of an explicit grey-world assumption (i.e., without assuming that the average spectral reflectance curve of environmental surfaces is flat) a great deal of research has been devoted to the achromatic case, for the good reason that the visual system seems well adapted to process the patterns of intensive changes generated by the interposition of transparent layers; patterns that differ in achromatic and chromatic cases (Da Pos 1999; Kramer and Bressan 2009, 2010). [2] The generalizability of any model developed in achromatic

[1] Transparency experienced in sensory perception provides a basis for the transparency metaphor, frequently encountered in fields as diverse as philosophy of mind (Hatfield 2011), linguistics (Libben 1998), and politics.

[2] Chuang et al. (2009) discuss the dominance of achromatic constraints in visualization.

conditions is important (Faul and Ekroll 2012); but perceptual organization issues are better analyzed in the grey world.

Achromatic transparency plays a special role in perceptual organization for the following reasons:

- it provides an ideal case for the application of the tendency to *Prägnanz*, which may be taken as the distinctive trait of the Gestalt theory of perception;
- under optimal conditions it appears as an organized outcome strongly constrained by geometric and photometric information, and highly functional, being formally equivalent to the solution of a pervasive inverse-optics problem;
- under suboptimal conditions it reveals the links between colour and form (a leitmotif of Gestalt psychology; Koffka 1935, pp. 260-264; see Section 5).

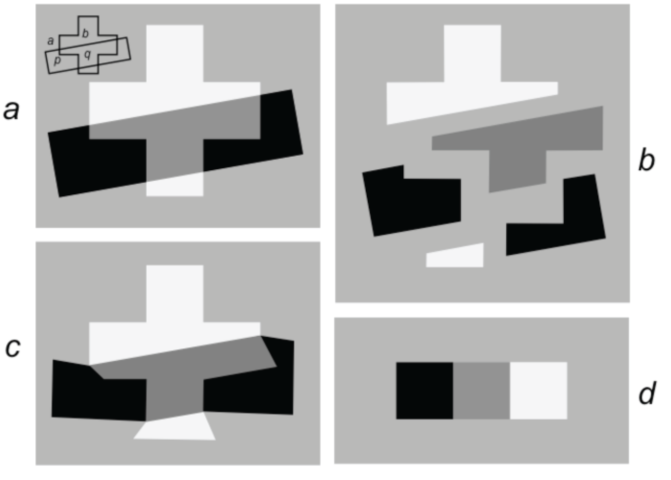

Figure 1. Apparent transparency (modified from Metzger 1936, Fig. 131). The pattern in *a* is usually perceived as a dark bar on top of a white cross (though an alternative perceptual solution is possible) and not as the mosaic of irregular shapes shown in *b*. The pattern in *c* is a control for the effect of figural organization on perceived colour: the adjacencies are kept constant, while good continuation of contours at junctions is eliminated. According to Metzger, transparency is not perceived in *d* because both black and white regions have a good shape and the addition of the grey region would not generate figures with a better shape.

Consider how Metzger (1936) set up the problem in Chapter 8 of *Gesetze des Sehens*, discussing a demonstration from Fuchs (1923). Figure 1*a* is normally perceived as a dark transparent bar on top of a white cross, not as the mosaic in Figure 1*b.* [3] The bar and the cross intersect in such a way that each "claims as its own" the superposition region, requiring the scission of its grey substance into two components that perceptual organization makes as similar as possible to bar and cross lightnesses. The double-belongingness of the superposition region depends, locally, on the good continuation of contours meeting at X-junctions and, more globally, on the improvement of form regularity. Metzger (1936) referred to his Fig. 27 to claim that the strength of such factors is well established by classical demonstrations with intertwined outline patterns (Köhler 1929; Wertheimer 1923). [4]

Figure 1*c* (not in Metzger 1936; drawn following Kanizsa 1955) is a control. All adjacencies in Figure 1*a* are maintained, but contours of neither the bar nor the cross keep a constant trajectory at X-junctions.

[3] The pattern in Figure 1*a* supports two transparency solutions. See Figure 8 for an analysis of bivalent 4-region patterns.

[4] In the Gestalt tradition the "apparent/real" dichotomy is used to stress that real transparency (i.e., a layer with non-zero transmittance) is neither necessary nor sufficient to support a transparency percept; apparent transparency is perceived in mosaics of opaque surfaces. Like for motion, the apparent/real dichotomy stimulates the search for the proximal conditions supporting the perception of transparency, independent of its veridicality.

The dark bar survives as a unit, being supported by the topological condition (see Section 2); but the sense of transparency is weakened, and the colour appearance of the superposition region is different from the one in Figure 1*a*.

Figure 1*d* displays a counterexample in which the same greys of Figure 1*a* are combined in a pattern that is perceived as a mosaic of three adjacent squares, though compatible – in principle – with the overlapping of two homogeneous rectangles, with the same front/back ambiguity and alternating transparency observable in the cross/bar display of Figure 1*a*.
Much of the theoretical weight of transparency depends on the colours seen when the intersection region belongs to both the dark bar and the light cross (panel *a*), rather than appearing as an isolated surface (panel *b*). Figural belongingness modulates the scission of the sensation (*Spaltung der Empfindung*; Hering 1879) and impacts on perceived intensity and colour appearance. Helmholtz (1910/1924, originally published in 1867) framed real transparency as a problem of recognizing the components of a light mixture, using knowledge acquired in ordinary environments in which at least the mixture of illumination and reflectance components is pervasive. In the Helmholtzian view, the same ratiomorphic process supports the discounting of illumination associated with the approximate constancy of opaque surface colours, the perception of shadows, the separation of filter properties from background properties, and analogous recovery problems. "Just as we are accustomed and trained to form a judgment of colours of bodies by eliminating the different brightness of illumination by which we see them, we eliminate the colour of the illumination also. […] Thus too when we view an object through a coloured mantle, we are not embarrassed in deciding what colour belongs to the mantle and what to the object." (Helmholtz 1924, p. 287)

Helmholtz's emphasis on observers' ability to evaluate light mixture components conflicts with the plain argument developed in Figure 1. The same light mixture sometimes is phenomenally split into components, sometimes not, depending on stimulus conditions. The discovery of conditions for the occurrence of phenomenal transparency (independent of its veridicality) is the goal of a long tradition of research oriented by Gestalt ideas (Fuchs 1923; Kanizsa 1955, 1979; Koffka 1935; Metelli 1970, 1974, 1975; Moore-Heider 1933; Tudor-Hart 1928), among which a special place is held by the idea that double-belongingness is a peculiar organization producing characteristic effects on perceived colour (Kanizsa 1955; Musatti 1953; Wallach 1935/1996).

Since transparency can be observed in line-drawing displays (Bozzi 1975), without specific photometric information, let us consider geometric conditions first.

2. Topological and figural conditions

Take the prototypical 4-region pattern in Figure 1*a*. To support perceived transparency, ***p*** and ***q*** regions should group together and form the layer; furthermore, each of them should group with the other adjacent region (***a*** and ***b***, respectively) and form a background surface partially occluded by the layer. That is, both ***p*** and ***q*** should belong to two units, subordinate to the whole configuration but superordinate to input regions, according to the intertwined pattern (**a**[**p**)(***q***]***b***). [5]

As suggested in the title of this section, the double-belongingness of two of the four regions depends on geometric constraints that have been articulated into topological and figural conditions (Kanizsa 1955, 1979; Metelli 1974, 1975, 1985b).

[5] An extended notation for the double-belongingness of ***p*** and ***q*** regions would be (***ap***)(***pq***)(***qb***). In the compact notation above the subunit corresponding to the transparent layer is marked by square brackets, while the background subunits are marked by round brackets.

2.1. Topological condition

The topological condition has been formulated as follows (Kanizsa 1955). To belong to two subunits each candidate region must be in contact with the other (reciprocal contact constraint) and with only one of the remaining regions (Figure 2). At the level of regions, the condition is satisfied when contours meet at a generic 4-side junction, even without good continuation at the contour level (Figure 1*c*).

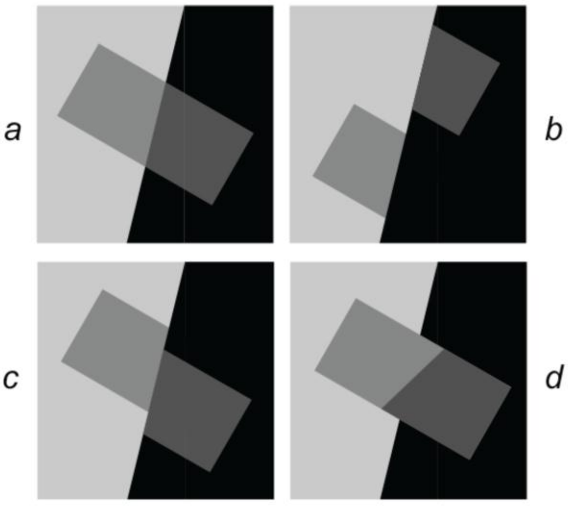

Figure 2. Topological condition (modified from Kanizsa 1955, 1979). (*a*) Canonical 4-region display fulfilling all geometric and photometric requirements. Panels *b*-*d* illustrate three ways in which the topological condition can be violated. (*b*) Regions that should be unified into a single layer are not in reciprocal contact, while touching both background regions. (*c*) The reciprocal contact constraint is fulfilled, but both candidate layer regions are in contact also with both background regions. (*d*) The topological condition is violated also when the inner contour of a unitary layer (i.e., the one that divides the two constituent regions) is not aligned with the contour that divides the background regions.

Kanizsa (1955, 1979) and Metelli (1975, 1985b) discussed various controversial configurations connected to the topological condition. Kanizsa (but not Metelli) concluded that the topological condition is necessary, though not sufficient. Panels *b* and *d* in Figure 2 depict violations that lead to the loss of the compelling transparency percept observed in Figure 2*a*. However, the broken layer depicted in Figure 2*c* does not completely forbid transparency, being consistent with common observations of shadows falling over a 3D step, with non coplanar background regions. Arguing that the topological condition is necessary, Kanizsa (1979, Fig. 8.9) claimed that transparency is hardly seen in Figure 3*a*. [6]

[6] You may disagree.

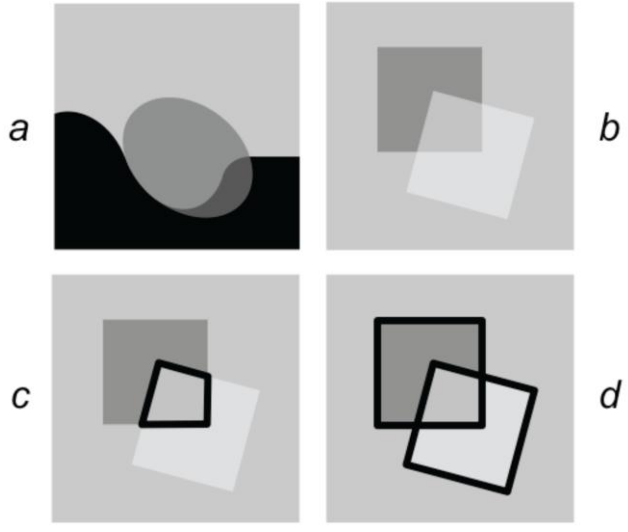

Figure 3. According to Kanizsa (1979) the pattern in *a* shows that the topological condition cannot be violated without destroying perceived transparency. Panel *b-d* (from Metelli 1985b) show the effect of thick outlines. The transparency perceived in *b* is destroyed by a thick outline surrounding the superposition region (panel *c*). A thick outline surrounding all regions can be integrated in the transparency percept (panel *d*).

Apart from being necessary or not, what is the meaning of the topological condition? Does it capture a figural constraint at the level of regions or does it relate to photometric conditions described in Section 3? The second hypothesis is supported by a manipulation of borders done by Metelli (1985b). Transparency of the oblique square in Figure 3*b* disappears if one eliminates the adjacency of to-be-grouped regions by superposing a thick outline on the borders of the intersection region (Figure 3*c*). Transparency is not blocked, however, if all regions are bounded by thick outlines that can become part of the transparency solution, with the upright square perceived on top of the oblique square (Figure 3*d*). The isolation effect in Figure 3*c* is reminiscent of the loss of the film appearance in a shadow whose penumbra is suppressed by a thick outline. [7]

2.2. Figural conditions

Figural aspects play a major role in transparency and, when strengthened by motion, can overcome contradictory photometric information. Kanizsa (1955, 1979) and Metelli (1974) emphasized the role of good continuation at X-junctions as the critical local factor supporting vivid impressions of transparency, other things being equal (i.e., once the topological condition is fulfilled and keeping the intensity pattern constant). However, they considered also more global figural factors, like the shape of regions.

Figural conditions for the double-belongingness of regions to be grouped into a layer agree with those that govern the segmentation of outline patterns and have been studied within a research tradition that goes from Wertheimer (1923) to the most recent developments of *Structural Information Theory* (SIT; Leeuwenberg and van der Helm, 2013). Wertheimer (1923/2012), commenting on his Figs. 33 and 34, observed that Fuchs (1923) utilized the same laws of unification/segregation when studying transparent surfaces in the period 1911-14 and found they strongly affect colour. Wertheimer's Fig. 33 is an outline version of Figure 3*b*, while Wertheimer's Fig. 34 is similar to Figure 1*d.* These and other famous outline patterns (like the pair of intertwined hexagons) support the idea that figural

[7] See discussions of Hering's shadow/spot demonstration in Metzger (1936/2006, Fig. 132) and Gilchrist (2006, p. 21).

segmentation crucially depends on the tendency towards the “good whole Gestalt” (Wertheimer 1923, p. 327; Wagemans, Chapter 1, section 3.2, this volume).

In an early application of SIT to visual and auditory domains, Leeuwenberg (1976; Leeuwenberg and van der Helm, 2013, Chapter 8) computed a measure of preference for pattern segmentation based on the ratio between the complexity of the mosaic solution and the complexity of the transparency solution. Using patterns like those in Figure 4 and coding only figural complexity (independently of photometric conditions), he obtained a high correlation between the theoretical preference measure and transparency judgements.

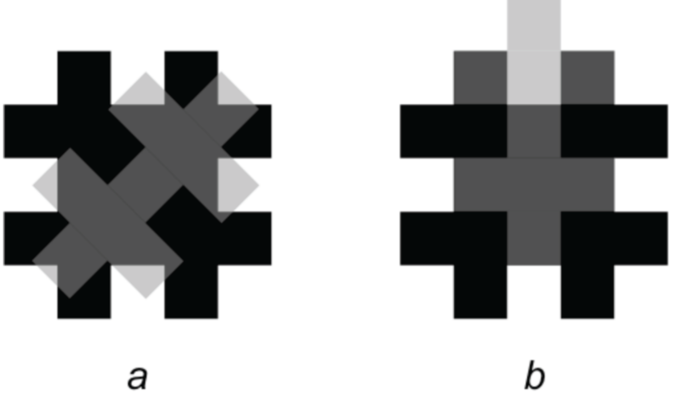

Figure 4. According to Leeuwenberg’s coding approach (1976) perceived transparency is predicted by a preference measure, with a value of 1 for the balance between mosaic and transparency solutions. Preference values are 11.90 in panel *a* and 0.56 in panel *b*. This measure takes into account only figural (not photometric) aspects.

Singh and Hoffman (1998) provided a major contribution to the idea that figural conditions go beyond the local good continuation at X-junctions. They used displays with X-junctions that preserved the local good continuation of background and layer contours (Figure 5) and asked observers to rate perceived transparency on a 1-7 scale. Observers were more sensitive to the size of turning angles at the extrema of curvature of the layer boundary when they were negative minima (panel *a*) than positive maxima (panel *b*). Average ratings ranged from 1.5 (close to perfect mosaic) to 6 for negative minima, and from 4 to 6 for positive maxima. Furthermore, Singh and Hoffman (1998) found that the proximity of the extrema of curvature to the background boundary (up to the coincidental arrangement shown in Figure 5) increased the detrimental effect on transparency ratings. Their results show that the competition between mosaic and double-belongingness solutions depends on properties like negative extrema, which are relevant for the parsing of shapes into parts (Singh, Chapter 25, this volume).

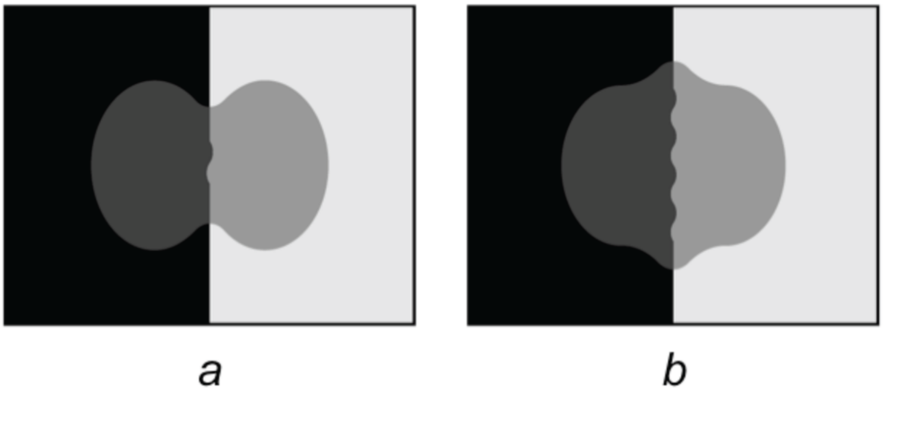

Figure 5. Coincidental alignment of background contour and extrema of curvature of the layer boundary. Singh and Hoffman (1998) found that negative extrema (minima, panel *a*) are more detrimental for perceived transparency than positive extrema (maxima, panel *b*).

All geometric factors known to affect relative depth may be effective in making the transparent layer more salient and in modulating the preference for one transparency solution when photometric conditions are ambivalent (see Section 3.2). Delogu et al. (2010) demonstrated that relative size can affect the depth stratification of transparent configurations. Binocular disparity (Nakayama et al. 1990; Anderson and Schmid 2012) and motion parallax (see Section 5) interact with transparency in complex ways.

2.3. Transparency in outline patterns

As regards intertwined outline patterns of the Wertheimer type (Brooks, Chapter 4, this volume; Elder, Chapter 7, this volume), one may wonder whether phenomenal transparency – in a generic sense – is involved in all cases in which a pattern of intersecting contours, in the absence of information carried by adjacent grey regions, is perceptually parsed into overlapping shapes. Double-belongingness of some enclosed regions is observed in both grey-region mosaics and outline patterns, but the transparency label would probably appear as stretched too far, if applied to all intertwined outlines.

Rock and Gutman (1981) used overlapping shapes involving the segmentation of contours and regions to relate attention and form perception, and made a point opposite to double-awareness, showing that perception of one figure may occur without perception of the other, despite the presence of all lines around the center of fixation. Object attention is based on segmentation (Scholl 2001; Driver et al. 2001) and can be limited in the number of overlapping planes the observer can be simultaneously aware of (Tyler and Kontsevich 1995; Fazl et al. 2008). [8]

However, phenomenal transparency should be qualified as something more than the simple experience of seeing overlapping figures or surfaces in depth. This type of stratification (supported by contour or texture information, motion parallax, or binocular disparity) might be a necessary condition for transparency, but phenomenal transparency should involve a characteristic colour appearance, different from the appearance of the same region when seen as part of a mosaic.

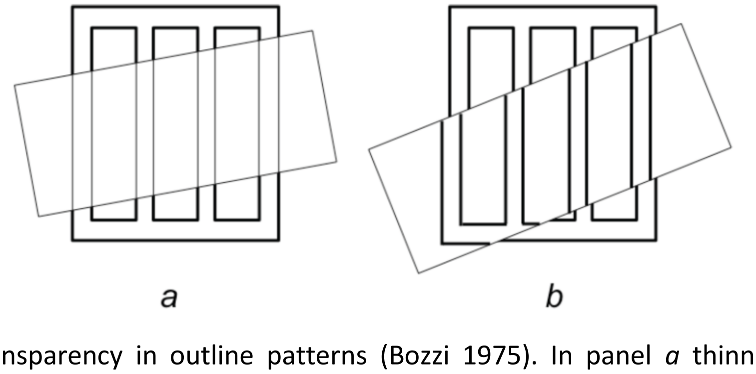

Figure 6. Transparency in outline patterns (Bozzi 1975). In panel *a* thinning all lines included within the oblique rectangle makes it appear foggy. In panel *b* the misalignment is perceived as the effect of a distorting superposed layer.

[8] Based on evidence from texture segmentation in motion transparency, Glass patterns, and stereopsis, such a number has been evaluated as equal to two (Edwards and Greenwood 2005; Gerbino and Bernetti 1984; Kanai et al. 2004; Mulligan 1992; Prazdny 1986), three (Weinshall 1991), four (Hiris 2001), and dependent on the cueing of attention (Felisberti and Zanker 2005).

This is the case in patterns like those in Figure 6, devised by Bozzi (1975) to demonstrate that the experience of an interposed layer or substance, capable of modifying the appearance of the background, can be obtained also in the limited and artifactual world of line drawings. Taken as a whole, Bozzi's demonstrations suggest that the perception of an interposed layer – at least in some conditions – amounts to the recovery of the causal history of shapes (Leyton 1992). The milky layer perceived in panel *a* accounts for the thinning of vertical lines, while the distorting glass perceived in panel *b* accounts for their lateral shift. Bozzi was well aware of the possibility that line thinning (panel *a*) may be equivalent to an intensity change, which would make at least some of his line drawings not less interesting, but similar to other effects involving assimilation and filling in. The degree of connection between Bozzi's outline displays portraying transparency and phenomena like achromatic neon spreading and flank transparency is debatable (Wollschläger et al. 2001, 2002; Roncato 2012). However, this objection does not apply to Figure 6*b* and other displays that depict a background transformation more complex than a simple change of intensity due to layer superposition. Line drawings are highly symbolic and transparency mediated by the specific transformations they can afford might go beyond the domain covered in this chapter.

3. Photometric conditions

To support transparency, the pattern of intensities of adjacent regions must satisfy a requirement that, at an abstract level, complements the good continuation of contour trajectories. The equivalent of a discontinuity in contour trajectory is an abrupt change of surface values (apparent transmittance, lightness, or others to be defined).

Consider contour trajectories in the neighbourhood of an X-junction originated by layer superposition. In general, background regions are divided by a continuous reflectance edge (R-edge), while the superposed layer and background regions are divided by a continuous transmittance-reflectance-illumination edge (TRI-edge). Following Nakayama et al. (1989) the latter edge is *intrinsic* to layer regions (it belongs to them) but *extrinsic* to regions seen as unoccluded background (it does not belong to them). Topological and figural conditions tell that both edges should be smoothly continuous at the X-junction.

Consider now intensities in the neighbourhood of the X-junction. Photometric conditions tell when one of the two crossing edges can be classified as a TRI-edge; i.e., when the intensity of each double-function region is consistent with the mixing of photometric properties of the adjacent background region and those of an ideally homogeneous layer resulting from the grouping of two adjacent double-function regions. Notions such as scission (Metelli 1970; Anderson 1997), vector analysis in the photometric domain (Bergström 1977, 1982, 1994), atmospheric transfer function (Adelson 2000) capture the same idea. A rather general term is *layer decomposition*, used by Kingdom (2011) to qualify brightness, lightness and transparency models – alternative to image filtering – that explain achromatic phenomena as a consequence of extracting components from each stimulus intensity (the invariant of alternative partitioning solutions). For historical and conceptual reasons let us illustrate the algebraic model proposed by Metelli (1970, 1974, 1975) which – despite limitations that will be pointed out – provides an effective frame of reference for the whole discussion on photometric conditions of transparency. [9]

[9] Kanizsa (1955, 1979) sometimes used the label "chromatic conditions" as a synonim of photometric conditions, discussing achromatic displays. To avoid confusions that would obviously arise in a chapter entitled "Achromatic Transparency", conditions related to region intensity (expressed as either reflectances or luminances) will be called "photometric".

3.1. Metelli's model

Metelli's model is derived from a simplistic case of real transparency – the episcotister setting utilized to manipulate light mixtures (Fuchs 1923; Koffka 1935; Moore-Heider 1933; Tudor-Hart 1928) – that is representative of a broad class of ecological settings, which in principle should consider more parameters (Richards et al. 2009), but – more importantly – has the virtue of being a simple and essential decomposition-and-grouping model.

As shown in Figure 1, a layer appears transparent only if partially superposed on a background that includes at least two regions of different reflectance. [10] Metelli provided a way of evaluating the amount of photometric information provided by a generic X-junction in which an R-edge intersects a TRI-edge. The R-edge is the simple boundary between two adjacent background regions, differing in reflectance but equally illuminated; while the TRI edge is a complex boundary arising from the superposition of a layer of variable transmittance and reflectance, and/or a change in illumination.

In the original model the input variables are the four reflectances that, in a cardboard display, mimic the light coming from two adjacent background surfaces **a** and **b**, and from the light mixtures **p** and **q**, obtained by rotating an episcotister (spinning disk with apertures and opaque sectors of variable reflectance) in front of background surfaces **a** and **b**, under the critical assumption that the episcotister and background surfaces are equally illuminated. [11] The fact that the situation referred to in the episcotister model does not involve physically transparent materials should not be seen as a problem. When an episcotister rotates faster than fusion speed, its effects on **p** and **q** intensities are equivalent to those generated by static layers as a thin veil or an optical filter. Neither the temporal (episcotister) nor the spatial (veil, filter) light mixtures follow the equations known as the episcotister model if the constraint of uniform illumination is not fulfilled; both should be described by the so-called filter model if the layer is very close or in contact with the background, as it actually looks in the flatland of impoverished 4-region displays (Beck et al. 1984; Gerbino 1994; Richards et al. 2009). [12]

Basically, the episcotister model takes regions grouped as (**a**[**p**)(***q***]***b***) according to figural constraints and verifies if **p** and **q** intensities are compatible with the constrained sum of two components described by the following equations:

$$\mathbf{p} = t\mathbf{a} + f \quad (1)$$
$$\mathbf{q} = t\mathbf{b} + f \quad (2)$$

[10] This formulation covers transparency perceived in the 3-region display, studied for instance by Masin (1984). His observers perceived as transparent a real filter suspended in front of a background that included a square projectively enclosed by the filter. However, the objective separation in depth was large enough to provide valid disparity information.

[11] In this chapter small letters are used for dimensionless numbers (reflectances **abpq** and other coefficients with meaningful values between 0 and 1) and capital letters for luminances (in Section 3.2). For further details see Gerbino et al. (1990) and Gerbino (1994). The transparency literature is full of different symbols for the same entities. I apologize for possible confusions.

[12] In the transparency literature, expressions like "episcotister model" and "filter model", or "episcotister equations" and ""filter equations", should not be taken as referring to a specific device (a spinning disk with open sectors vs. a piece of smoked glass), but to two extreme types of background illumination: in the so-called episcotister model the background is illuminated exactly like the layer (a condition easily obtained if the layer is suspended in mid air, far away from the background); in the so-called filter model the background is illuminated only through the layer (a condition which quite frequently occurs when a filter is in contact with the ground).

Equations 1 and 2 make clear that the episcotister model is a straightforward decomposition-and-grouping model. Each intensity of a region to be grouped into the layer is reduced to the sum of a multiplicative component and an additive component (the scission aspect): the first is the constant fraction *t* of the corresponding background region; the second is a common component that – whatever the *t* value between 0 and 1 – attenuates the background contrast **a/b**.

Equations 1 and 2 describe how **a** and **b** intensities are modified by a rotating episcotister with an open sector of size *t* and an effective reflectance *f*, equal to the product of the size of the complementary solid sector (1-*t*) by its reflectance *r*. Since both *t* and *r* are proper fractions (*t* is the relative size of the opening of the episcotister and *r* is a reflectance), neither can be smaller than zero or larger than 1.

Equations 1 and 2 refer to direct optics. For instance, knowing background reflectance **a**, filter transmittance *t* and filter reflectance *r*, one can derive the effective reflectance of the superposition area **p**. However, such a system of two equations becomes a useful psychophysical model if one realizes (as Metelli did) that it provides unique solutions for both *t* and *r*, constituting a plausible inverse-optics model for the recovery of layer properties (not explicit in the stimulus) from the pattern of input values (Marr 1982, pp. 89-90). Relevant solutions are as follows:

$$t = (\mathbf{p} - \mathbf{q}) / (\mathbf{a} - \mathbf{b}) \qquad (3)$$
$$r = (\mathbf{aq} - \mathbf{bp}) / [(\mathbf{a} + \mathbf{q}) - (\mathbf{b} + \mathbf{p})] \qquad (4)$$
$$f = (\mathbf{aq} - \mathbf{bp}) / (\mathbf{a} - \mathbf{b}) \qquad (5)$$

Taking the episcotister as a physical model of real transparency Metelli proposed that layer transmittance and reflectance are perceived in the same way in which the reflectance of an opaque background surface is perceived as its lightness. Layer transparency (perceived transmittance, increasing with *t*) and layer lightness (perceived reflectance, increasing with *r*) are derived from the pattern of stimulation.

The hypothesis that perceptual dimensions of transparency parallel the physical properties of the layer is quite controversial (Albert 2006, 2008; Anderson 2006; Anderson 2008; Anderson et al. 2006; Anderson et al. 2008a, 2008b; Masin 2006; Singh and Anderson 2002, 2006). According to Kingdom (2011, section 9) further research is needed to identify the appropriate perceptual dimensions and the best methods for obtaining valid data from observers. However, as remarked by Anderson et al. (2008a, p. 1150), researchers should not expect that all variables included in generative physical models like Equations 1 and 2 have a perceptual meaning. Furthermore, they should consider the possibility that perception is sensitive to other variables. For instance, solutions for *t*, *r*, *f* (Equations 3, 4, 5) are more complex than the simple intensity ratio available at each image boundary; while attenuation of border contrast is probably the most salient physical consequence of layer superposition. [13] Note that *t* and *r* values, against intuition, are not related to contrast attenuation in a simple way (Figure 7).

[13] The attenuation of border contrast is also behind the notion of *veiling luminance*, a hybrid term that combines the phenomenal transparency of a metaphorical veil with a physical measure of input intensity (Gilchrist, 2006, pp.196-197). When spontaneously perceived as a veil, added light is experienced as the cause of the reduced visibility of otherwise well-contrasted borders (a case of real transparency without X-junctions).

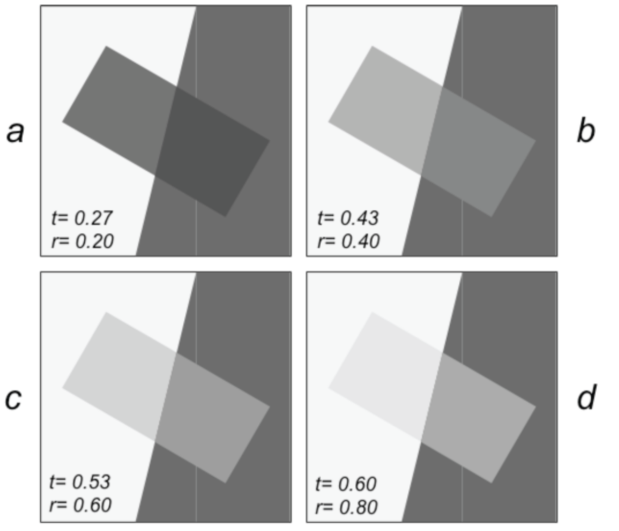

Figure 7. The four panels illustrate that, keeping background intensities constant (***a***= 0.90; ***b***= 0.10), approximately the same attenuation of background contrast (**p/q**≅ 0.25 **a/b**) is compatible with different pairs of *t* and *r* values (shown in each panel). Intensities of ***p*** and ***q*** regions are as follows: (*a*) ***p***= 0.12; ***q***= 0.05; (*b*) ***p***= 0.39; ***q***= 0.17; (*c*) ***p***= 0.61; ***q***= 0.27; (*d*) ***p***= 0.76; ***q***= 0.34.

3.2. Reflectances or luminances?

Clearly, the choice of reflectances as input variables is controversial and raised several discussions (Beck 1985; Beck et al. 1984; Gerbino 1994; Metelli 1985a; Masin 2006). Reflectances are distal values, and a model should express perceptual values as a function of proximal, not distal, values. On the other hand, under homogeneous illumination reflectances can be taken as luminances in arbitrary units, making the distinction irrelevant. Another type of criticism refers, instead, to the possibility of taking lightnesses (i.e., perceived reflectances derived from a transformation of luminances) as the input for the model. This approach is theoretically consistent with the existence of a stage in which all four regions of the canonical display are represented as opaque surfaces, each with its own lightness, and of a subsequent stage in which a better solution is achieved (Rock 1983, pp. 138-139).

An unfortunate implication of the use of reflectances is Metelli's idea that *r*= 1 constitutes an effective upper boundary for transparency. Reformulating the episcotister model in terms of luminances (Gerbino 1988, 1994; Gerbino et al. 1990) helps to understand that this constraint can be relaxed. Using luminances as input values, Equations 1 and 2 change as follows:

$$\mathbf{P} = t\mathbf{A} + \mathbf{F} \quad (6)$$

$$\mathbf{Q} = t\mathbf{B} + \mathbf{F} \quad (7)$$

In Equations (6) and (7) also the additive component **F** is a luminance, equal to (1-*t*) $r\,\mathbf{I}_e$, where $\mathbf{I}_e$ is the illumination falling on the episcotister, in principle different from the illumination $\mathbf{I}_b$ falling on background regions whose reflectances are ***a*** and ***b***.[14] Following the inverse-optics logic there is no reason to reject values of the additive component **F** larger than (1-*t*) $\mathbf{I}_b$, (i.e., *r*= 1), since they are compatible with more illumination falling on the layer than on the background. In principle one could decompose even smaller **F** values as involving an increase of the illumination on a layer with *r*< 1. But this solution would be against the minimum principle (which leads to a decomposition with uniform illumination, unless required by specific stimulus information).

[14] As anticipated in *Footnote 11*, capital letters are used for luminances and light intensities, while small letters indicate dimensionless numbers (reflectance and transmittance coefficients).

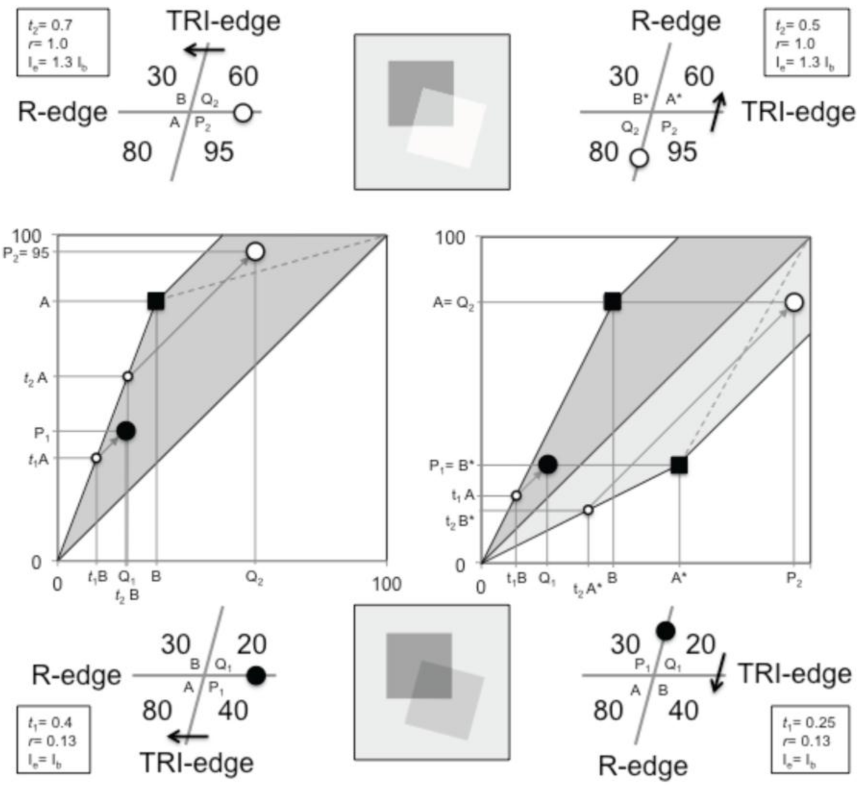

Figure 8. Transparency solutions for two 4-region patterns are visualized in diagrams adapted from Remondino (1975). Coordinates represent luminances in arbitrary units. Both 4-region patterns are compatible with two transparency solutions, corresponding to two different *t* values. The component *r* has a low value (r= 0.13) in both solutions for the bottom pattern; while it exceeds the r= 1 boundary (dashed line) in both solutions for the top pattern, Each shaded trapezoidal region of the two diagrams represents the space of valid **PQ** luminance pairs for a given **AB** pair (square symbol). Such a space is actually open in the direction of higher **PQ** values, since the additive component (visualized by the projection of the oblique arrow on each axis) can take any positive value, if constraints on illumination are relaxed. **PQ** pairs are shown in the two diagrams as circular symbols, filled for the pattern at the bottom and empty for the pattern at the top.

Photometric conditions of the episcotister luminance model are conveniently represented in the diagram devised by Remondino (1975). Figure 8 includes two diagrams, to represent two transparency solutions, one for each of the two edges crossing at the X-junction, for two 4-region patterns having in common two luminances (30 and 80, in arbitrary units). In general, photometric conditions for the TRI-edge can be satisfied for both edges, only one, or none. In the pattern at the bottom the two solutions correspond to the following **APQB** orderings: (80, 40, 20, 30) and (80, 30, 20, 40), with t= 0.4 and 0.25, respectively, and r= 0.13 in both cases. Both transparency solutions of the pattern at the top violate the r< 1 constraint, but can be interpreted as cases in which a layer made of perfectly white particles is more illuminated than the background ($\mathbf{I}_e$= 1.3 $\mathbf{I}_b$, if r= 1). The aspect of the diagram with the most prominent theoretical meaning is the shaded region representing the set of **PQ** values compatible with a given **AB** pair and with the constraints of the episcotister luminance model.

3.3. Are X-junctions and four regions indispensable?

These are two different questions, of course. An X-junction implies four regions, but four regions can be effectively arranged without X-junctions (for instance, as stripes in a row; Da Pos 1999).

Furthermore, transparency can be obtained in double-inclusion patterns of three regions, without X-junctions, though stereo and relative motion help a lot in such a limiting case (Masin 1986). At low contrast, transparency can be perceived also in 2-region displays (Masin and Idone 1981).
As regards the indispensability of X-junctions, Masin (2006) found that transparency in a striped pattern **APQB** can be vivid, if supported by coherent motion of **AP** and **QB** boundaries, and that transparency ratings did not differ from those obtained in a classic 4-region display with X-junctions. This piece of evidence is consistent with the fact that, given four intensity values around an X-junction, any of the four ratios of adjacent luminances is redundant and can be derived from a well-taken product of the others. In the case of the **APQB** pattern the **A/B** ratio of non-adjacent luminances could be obtained as a product of ratios **A/P**, **P/Q**, **Q/B** (following the product of sequential ratios approach applied in Retinex; Land and McCann 1971).

3.4. Shadows, transparency, and constancy
As stressed by Adelson (2000) in his notion of atmospheric transfer function, a decomposition model like Metelli's makes clear the continuity between shadows and transparency. In a less optimistic way, one might say that the model cannot discriminate between a shadow and a transparent layer with zero reflectance or without illumination falling on it. In all three cases the additive component is zero. Perceptually, the distinction between a shadow and a transparent layer is not sharp at all. [15] If the essence of phenomenal transparency is the sense of "seeing through", shadows (like episcotisters with a black opaque sector; Koffka 1935; Tudor-Hart 1928) are the best transparent layers one can experience. Particularly when their boundary is sharp, shadows have a clear shape that intersects background shapes and can be easily segmented (Mamassian et al. 1998).

Shadows and layers share the problem of constancy; i.e., the perceptual invariance of object properties despite stimulus change. Perfect decomposition of layer regions (including shadows as a limiting case) should lead to complete colour constancy of surfaces seen through the layer, as well as to complete constancy of the transparent layer. The phenomenon that probably better embodies the interplay between shadows, transparency, and constancy is the illusion by Anderson and Winaver (2005; Gilchrist 2005). An important implication of constancy of surface colour seen in a cast shadow or through a transparent layer was studied by Rock et al. (1992), who found that similarity grouping is not based on luminances but on lightness values, consistent with early layer decomposition. So far, research on transparent layer constancy (Faul and Ekroll 2012; Gerbino et al. 1990) has provided good support for the layer decomposition approach, despite the methodological limitations of some studies pointed out by Kingdom (2011). However, more experiments considering both types of constancy in comparable conditions are necessary.

4. Effects of transparency

Transparency can be conceived of as the effect of appropriate stimulus conditions, but also as the cause of specific changes in other perceptual properties. Kanizsa (1955) articulated this logic referring to Figure 9*a*, an ambiguous pattern supporting either an occlusion solution (a light lamina with holes in front of an oblique opaque bar) or a transparency solution (a milky rectangular filter in front of a rectangle with holes). The dominance of one solution over the other depends on the relative intensities of the three regions (Ripamonti and Gerbino 2001); but when conditions are such that both solutions are easily perceived, a clear effect of form organization on colour is observed. In the

[15] Metelli (1985) reminded us that the devil – notoriously an excellent observer – treats Peter Schlemihl's shadow as a thin mantle laying on the terrain: "He shook my hand, knelt down in front of me without delay, and I beheld him, with admirable dexterity, gently free my shadow, from the head down to the feet, from the grass, lift it up, roll it together, fold it, and finally tuck it into his pocket." (Chamisso, *The Wonderful History of Peter Schlemihl*).

occlusion solution (that may be primed by panel *b*, where intensity conditions do not favour transparency) the oblique bar is amodally completed but its modal parts have a hard surface colour. In the transparency solution the oblique bar is similar to the one in panel *c*, where the white outline makes the bar unambiguously in front. Coming in front is associated with a distinctive change in colour appearance. The bar appears modally completed in front by the addition of illusory contours and all its surface acquires a milky appearance (Van Lier and Gerbino, Chapter 11, this volume).

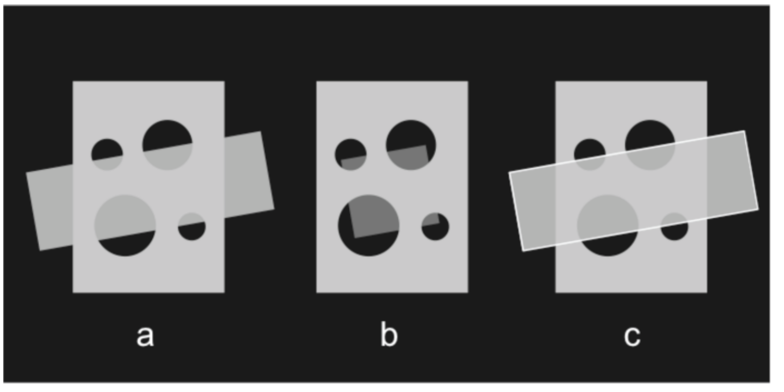

*Figure 9***.** The ambiguous three-intensity pattern in panel *a* (Kanizsa 1955) can be perceived as a light lamina with four holes in front of an oblique rectangle (like in panel *b*) or as a transparent oblique rectangle in front of a lamina with holes (like in panel c). The addition of a thin outline disambiguates the transparent layer, which takes on a definite milky appearance. The same colour appearance is observed in *a*, when the oblique rectangle appears in front.

There are two theoretically important points. First, the specific colour appearance of transparent surfaces cannot be explained by image properties only, given that the image remains the same during occlusion/transparency reversals. Second, changes are consistent with scission: an invariant stimulus-specified quantity splits into a layer component and a background component. Kanizsa (1955) remarked that the measurement of such components is made difficult by opposite tendencies in different observers: some focus their attention on the transparent layer in front, some on surfaces seen through the layer.

As regards other effects (or at least, other couplings involving transparency) Kersten et al. (1992) provided a nice demonstration of the interplay between transparency and rotation in depth. Gerbino (1975) found that shrinkage by amodal completion extends to rectangles partially occluded by a layer of variable transparency, and its amount correlates with the perceived opacity of the layer. Sigman and Rock (1974; Rock 1983, p. 171) demonstrated that an opaque occluder, but not a transparent object, vetoes the perception of stroboscopic motion, according to the idea that this type of apparent motion is mediated by perceptual intelligence. Moving from the observation that transparency can be perceived in low-contrast disk-surround displays (Masin and Idone, 1981), Ekroll and Faul (2012a, 2012b, 2013) argued that the perception of transparency can provide a unifying account of simultaneous colour contrast phenomena. [16]

5. Transparency and motion

There are at least two logical intersections between transparency and motion. First, some motion configurations are perceptually segregated into different entities (typically, overlapping planes) that

[16] Musatti (1953) articulated a theory of simultaneous colour contrast, based on scission of the proximal colour, in which the "equalizing" common component was primary.

involve the fundamental feature of phenomenal transparency; i.e., perception of one surface through another. In this case photometric information is not critical. Second, transparency in grey-level images can be instantiated or enhanced by motion of the TRI-edge relative to the E-edge. The point of contact between the two research lines is represented by the effect of luminance constraints on motion segmentation in plaid patterns (Stoner et al. 1990; Trueswell and Hayhoe 1993).

5.1. Motion transparency

In random dot kinematograms (RDK), grouping by common fate leads to the segmentation of textured overlapping surfaces. This phenomenon is usually called motion transparency and has been intensively utilized to study motion mechanisms (Braddick and Qian 2001; Curran et al. 2007; Durrant et al. 2006; Meso and Zanker, 2009; van Doorn and Koenderink 1982a, 1982b), the maximum number of independent planes that the visual system can effectively segregate (Edwards and Greenwood 2005; Gerbino and Bernetti 1984; Mulligan 1992), depth ordering (Schütz 2012), global vs. local motion (Kanai et al. 2004) and directional biases (Mamassian and Wallace 2010).

Transparency perceived in RDK is a by-product of grouping by motion and does not involve layer decomposition with colour changes. However, figure/ground stratification is correlated with small but reliable effects on lightness and perceived contrast. As noted since Rubin (1921) and demonstrated by Wolff (1934; Gilchrist 2006) the figure appears more contrasted than the ground; and perceived contrast within the figure is higher than perceived contrast within the ground (Kanizsa 1979). Since attention is normally directed towards the figure, one should also consider that attention can enhance contrast, as postulated by James (1890) and demonstrated in several studies (Barbot et al. 2012; Carrasco et al. 2000; Prinzmetal et al. 2008; Treue 2004).

5.2. Kinetic transparency in grey-level patterns

The emergence of perceived transparency can be facilitated by relative motion, also in grey-level patterns that otherwise would be perceived as mosaics. Masin (2006) used motion to support transparency in 4-region patterns without X-junctions. The basic effect was observed by Wallach (1935; English translation in Wuerger et al. 1996) in his pioneering analysis of the aperture problem (Bruno and Bertamini, Chapter 33, this volume) and Musatti (1953; Kanizsa 1955).[17] Transparency effects induced by motion and clearly involving colour changes occur in kinetic neon color spreading (Bressan and Vallortigara 1991; Bressan et al. 1997), in the so-called “flank transparency” (Wollschläger et al. 2001, 2002), and in various stereokinetic phenomena (Vezzani et al., Chapter 34, this volume; Zanforlin and Vallortigara 1990; Zanforlin 2006).

6. Conclusion

Principles of perceptual organization prove to be an important source of inspiration for the understanding of phenomenal transparency. Concern for the physical plausibility of transparency models has sometimes obscured the fundamental fact that notions like scission and layer decomposition, combined with grouping by surface colour similarity and contour good continuation satisfactorily account for perception. Interested readers will find extensive treatments of other aspects of phenomenal transparency in recent empirical and theoretical papers (Faul and Ekroll 2011, 2012; Kingdom 2011; Kitaoka 2005; Koenderink et al. 2008, 2010; Richards et al. 2009). Important evidence on the neural mechanisms related to the assignment of border ownership in transparency patterns has been found by Qiu and von der Heydt (2007).

[17] Musatti (1953, p. 555) attributed to Metzger the honour of first observing transparency in stereokinetic displays. Metzger mentioned the effect in the second edition of *Gesetze des Sehens* (1953) and discussed (1955) the paradoxical fact that stereokinesis can make a disk transparent and sliding over another also when the colour of the superposition region is physically unplausible, as later reported by Hupé and Rubin (2000).

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