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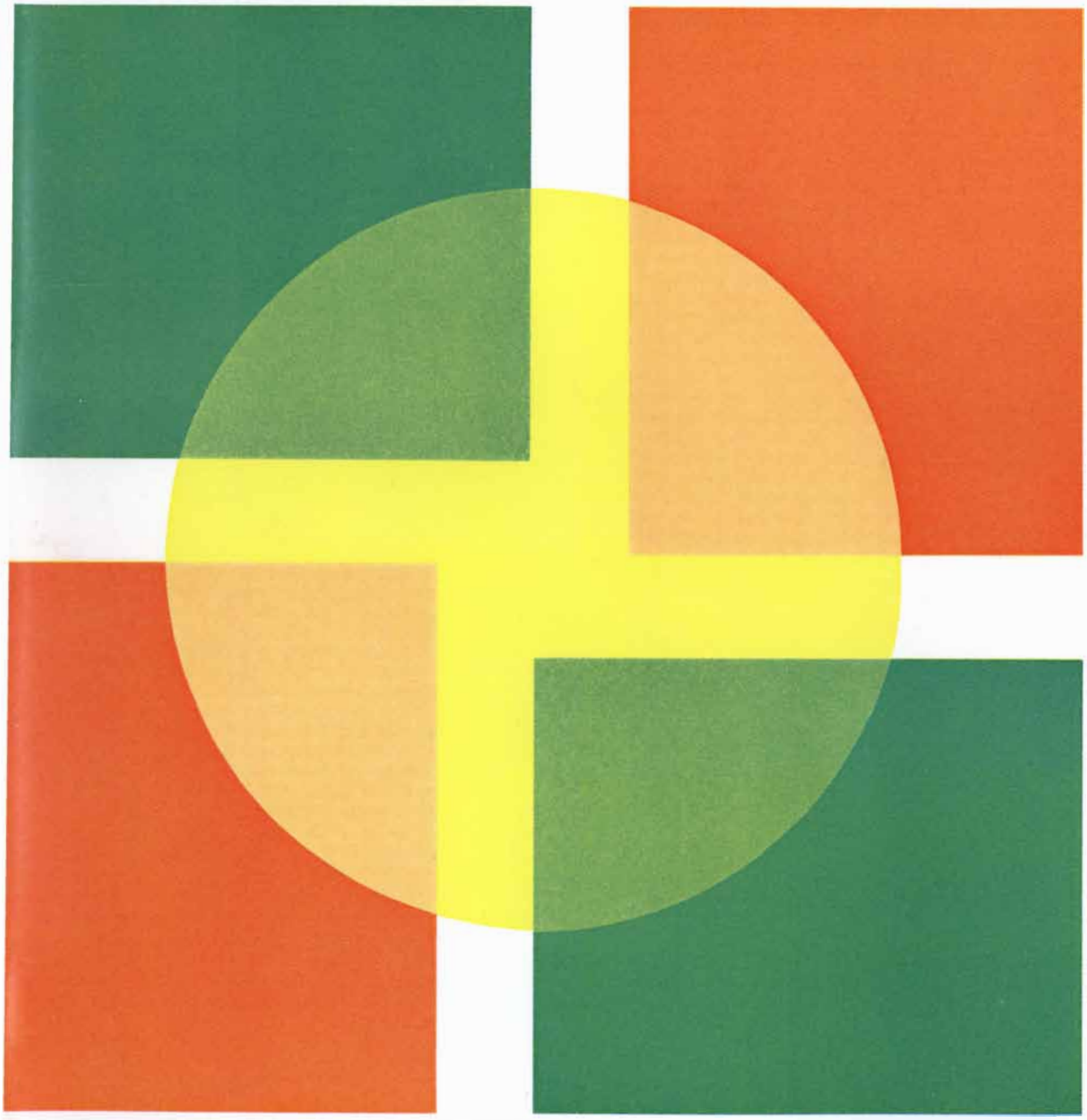
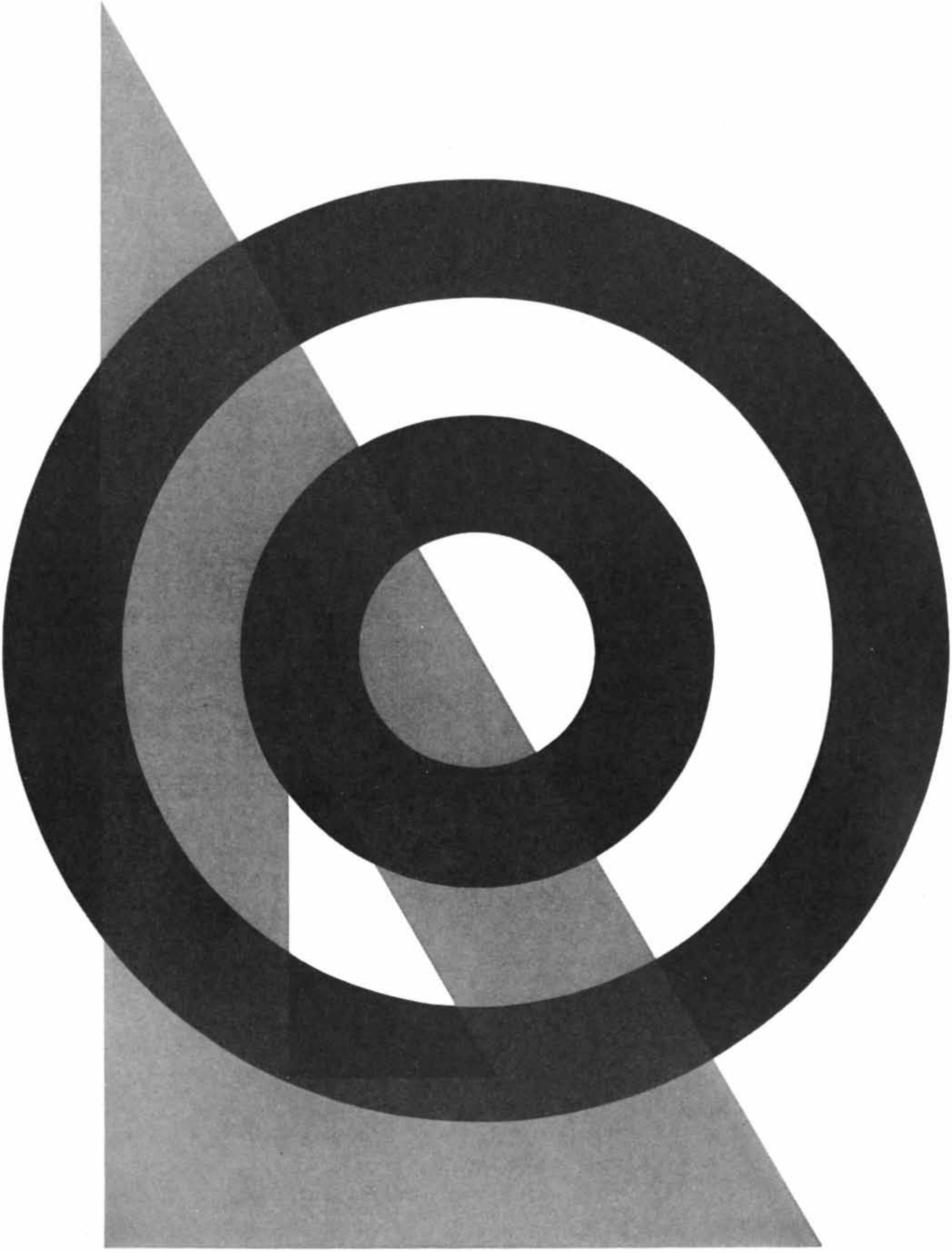


PERCEPTION OF TRANSPARENCY

ONE DOLLAR

April 1974



TRIANGLE IS PERCEIVED as being transparent and on top of the black and white concentric circles even though no elements of the illustration actually are physically transparent. The triangle is a mosaic composed of individual light gray and dark gray sections.

The Perception of Transparency

Certain mosaics of opaque colors and shapes give rise to the impression of transparency. A simple theoretical model predicts the conditions under which perceptual transparency will occur

by Fabio Metelli

What do we mean when we say that something is transparent? Actually the term has two meanings. If we are referring to the fact that light can pass through a thing or a medium, then the meaning of "transparent" we intend to convey is physical; if, on the other hand, we mean to say that we can see through something, then the meaning we intend to convey is perceptual. The distinction would not be very important if physical and perceptual transparency were always found together. Such, however, is not the case. Air is physically transparent, but normally we do not speak of "seeing through" it. Nor do we always perceive plate glass doors, since we occasionally run into them. It seems useful, therefore, to give a more precise definition of the perception of transparency: One perceives transparency when one sees not only surfaces behind a transparent medium but also the transparent medium or object itself. According to this definition, air and plate glass are not perceptually transparent unless there is fog in the air or there are marks or reflections on the glass.

The fact that physical transparency is not always accompanied by perceptual transparency can be demonstrated. Take a square of colored transparent plastic and glue it onto a larger square of black cardboard. Provided that the layer of glue is spread evenly, the plastic no longer is perceived as being transparent; it appears to be opaque. Changing the color of the cardboard, say from black to white, does not alter the effect [*see top illustration on next page*].

There also are instances where physical transparency is absent and perceptual transparency is present. Wolfgang Metzger of Münster has shown that mosaics of opaque cardboard can give rise to a perception of transparency even though there are no elements in the mosaic that are physically transparent [*see second illustration from top on next page*]. These two examples make it clear that physical transparency is neither a necessary nor a sufficient condition for the perception of transparency. Physical transparency cannot explain perceptual transparency.

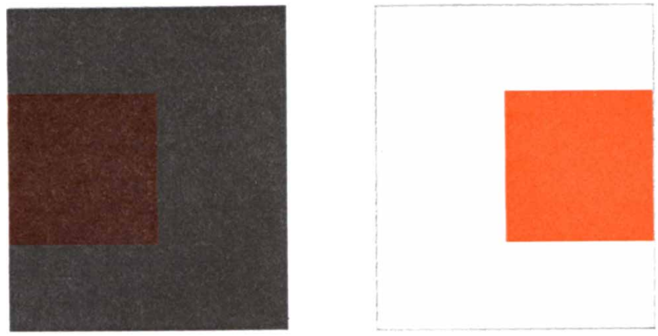
What causes perceptual transparency? As with other visual phenomena, the causes must be sought in the pattern of stimulation and in the processes of the nervous system resulting from retinal stimulation. Light reaches the retina only after having passed through several transparent mediums (air and the transparent mediums of the eye). The input to the retina, however, does not contain specific information about the characteristics of the transparent layers through which the light has traveled and been filtered. The perception of transparency is thus not the result of filtration; it is a new fact originating in the nervous system as a result of the distribution of the light stimuli acting on the retinal cells.

Perceptual transparency depends on the spatial and intensity relations of light reflected from a relatively wide field and not on light reflected only from a local area. This can be demonstrated by juxtaposing two sets of squares that do not appear to have any transparent areas [*see third illustration from top on next page*]. The juxtaposition produces a change from apparent opacity to transparency even though the light reflected from each region has not changed.

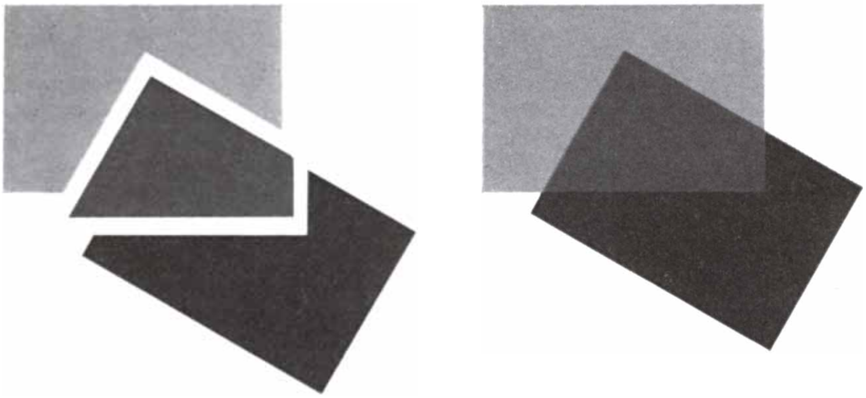
The conditions under which transparency is perceived have been studied by several eminent investigators, beginning in the 19th century with Hermann von Helmholtz and his contemporary Ewald Hering. They were at odds on almost all points. In his treatise on physiological optics Helmholtz described the perception of transparency as "seeing through" and studied it with a simple device in which images of two strips of paper of different colors were perceived one behind the other. The colors were superposed by reflection and transparency. Similar dual images can be found on windows under certain conditions, for example in the evening when one looks outside and sees both the reflection of the illuminated room and the external landscape.

Hering denied the possibility of seeing one color behind another. He argued that when light reflected by two different colors reaches the same retinal region, an intermediate or fusion color will be perceived. He supported his argument with new observations. When an observer concentrated only on the region where the two color images were superposed, just one color, the fusion color, was perceived.

In 1923 the German psychologist W. Fuchs was able to solve the Helmholtz-Hering controversy. He showed that both colors are perceived only when the transparent object and the object seen through it are perceived as independent objects. If the region of superposition of the two objects is isolated (even if it is just by the attitude of the observer), then only the fusion color is perceived. In the following years important findings were made by the Gestalt psychologist Kurt Koffka and some of his students at Smith College. B. Tudor-Hart showed that transparency on a totally homogeneous ground is not possible (for example the transparent plastic on a black cardboard). In 1955 Gaetano Kanizsa of the University of Trieste pointed out that whereas investigators had been concentrating only on the region of superposition of two figures, the conditions for perceiving transparency also applied

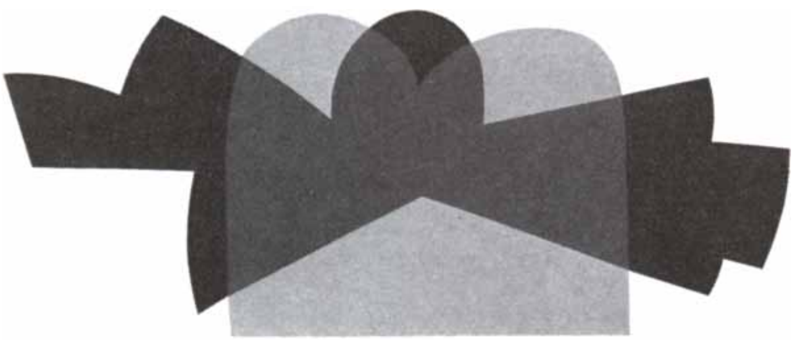


COLORED SQUARES OF TRANSPARENT PLASTIC glued onto a black cardboard (*left*) or a white one (*right*) no longer appear to be transparent. This demonstrates that perceptual transparency is not possible when the underlying field is homogeneous.



MOSAIC METHOD for constructing a figure with perceptual transparency out of opaque pieces is depicted. There is a strong impression of transparency in the central region where the two rectangles overlap. The method was originally developed by Wolfgang Metzger.

CHANGE FROM OPACITY TO TRANSPARENCY is obtained when the two figures depicted in the illustration at the top of the page are juxtaposed in the manner shown here.



TRANSPARENCY EFFECT is much more evident on an opaque figure than on the background, but conditions required to perceive transparency are the same in both instances.

to the regions in which the background could be seen through the transparent surface. The fact that this point had been neglected indicates that transparency on a figure is much more evident than transparency on the background [*see bottom illustration at left*].

The early investigators worked with filters or transparent objects, but after it became clear that physical transparency is not essential for the perception of transparency the use of physically transparent objects was generally abandoned. A number of investigators worked with the episcotister: a wheel with sectors cut out. The wheel generates a strong impression of transparency when it is rotated at high speed [*see top illustration on opposite page*]. This technique enables the experimenter to independently vary the size of the missing sectors (which affects the degree of transparency) and the color of the remaining sectors (which determines the color of the transparent layer).

In my own work I have used the mosaic method developed by Metzger because it offers a means of independently varying the color, the size and the shape of each region of a configuration. With this method it is easy to demonstrate that transparency depends on form as well as on color [*see middle illustration on opposite page*].

There are three main figural conditions for perceiving transparency in overlapping figures: figural unity of the transparent layer, continuity of the boundary line and adequate stratification. Let us examine each condition in turn.

When the unity of the central region of a transparent shape is broken, the perception of transparency is lost [*see bottom illustration on opposite page*]. On the other hand, modification of the shape that does not break up figural unity will not cause transparency to be lost. Figural unity of the transparent layer alone, however, is not sufficient to give rise to the perception of transparency. The boundary that divides the figure into two regions (one light and one dark) must be perceived as belonging to the opaque regions. A break in the continuity of the boundary line where it intersects the transparent layer can destroy the transparency effect. Abrupt changes in the boundary at points other than this intersection do not hinder the perception of transparency [*see top illustration on page 94*].

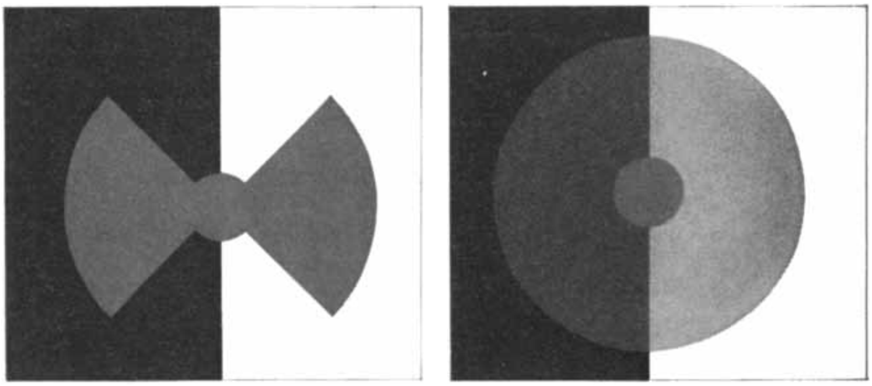
We have defined the perception of transparency as seeing surfaces behind a transparent medium or object. This means that the layer having the conditions necessary to become transparent must be located on or above the surface of the opaque object. It is not sufficient, however, for one surface to be perceived as being on top of another in order to obtain the effect of transparency. It is possible to perceive different strata in figures where no transparency is seen [*see bottom illustration on next page*]. In order to create adequate stratification for transparency the underlying regions must appear to meet under the whole of the transparent layer.

Let us take as a model a figure in which the underlying region is composed of two squares, one black and one white. On these are superposed two smaller squares, one light gray (over the white) and the other dark gray (over the black) [*see illustration on page 96*]. When all the figural and color conditions for transparency are met, then the gray regions appear to be a single transparent surface. (Unbalanced transparency is possible, but here we shall for the most part discuss cases where the transparent layer appears to be uniform.)

How is it that two shades of gray give rise to the same shade of gray in the transparent layer that is perceived? This phenomenon has been described as a case of perceptual scission, or color-splitting. The original gray is called the stimulus color. With the perception of transparency the stimulus color splits into two different colors, which are called the scission colors. One of the scission colors goes to the transparent layer and the other to the surface of the figure below. In 1933 Grace Moore Heider of Smith College formulated the hypothesis (and gave an experimental demonstration) that there is a simple relation between the stimulus and the scission colors: when a pair of scission colors are mixed, they re-create the stimulus color.

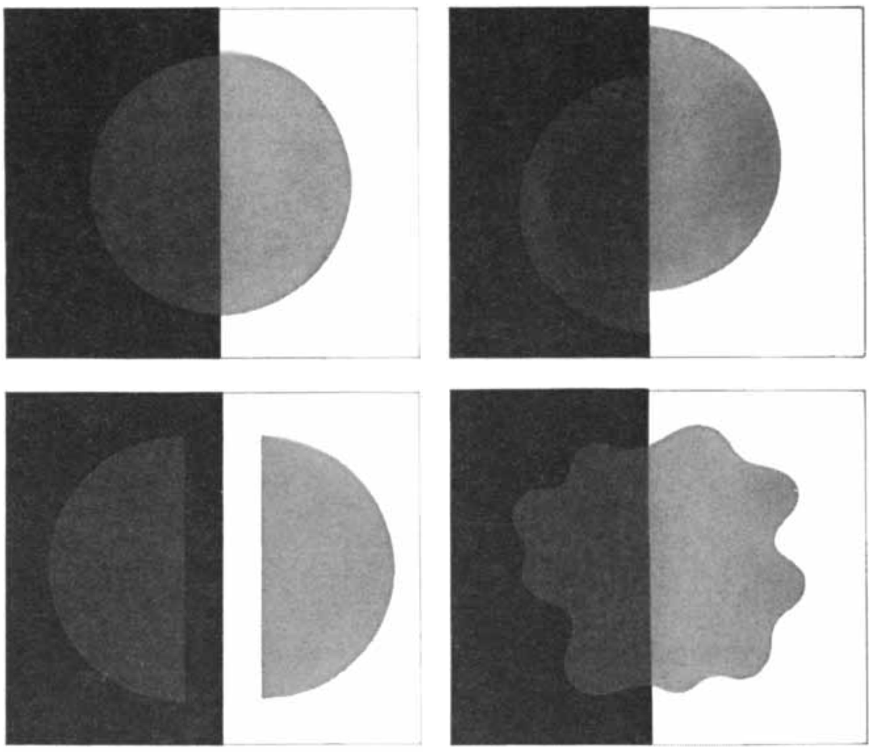
The process of color scission works in a direction opposite to that of color fusion. The law of color fusion, also known as Talbot's law (although it actually goes back to Isaac Newton), enables us to predict what color will be perceived when two colors are mixed. The same law, as Heider demonstrated, can be used to describe the color scission that gives rise to transparency. Since measuring chromatic colors such as yellow, red and blue is relatively complex, we shall limit our discussion to the achromatic colors (white, gray and black), which can be measured in a simple way. The achromatic colors vary only in one dimension: lightness. They can be defined by their albedo, or coefficient of reflectance: the percentage of light they reflect.

Every surface absorbs and reflects



EPISCOTISTER is a wheel with cutout sectors (*left*). When the wheel is rapidly rotated with a suitable background behind it, a strong impression of transparency is created (*right*).

PERCEIVED TRANSPARENCY of the gray circle (*figure at left*) can be abolished either by an abrupt change of form (*middle*) or by an alteration in the color relations (*right*).



FIGURAL UNITY OF THE TRANSPARENT LAYER is a necessary condition for perceiving transparency (*top left*). When the unity of the shape is broken, the transparency effect is lost. Changes in the shape, however, do not destroy transparency (*bottom right*).

part of the light falling on it. An ideal white that reflects 100 percent of the light falling on it would have a reflectance of 100; an ideal black that absorbs 100 percent of the light falling on it would have a reflectance of zero. These limits are never reached; a piece of white cardboard typically has a reflectance of about 80 and a piece of black cardboard a reflectance of about 4. Grays have a reflectance ranging from 4 to 80.

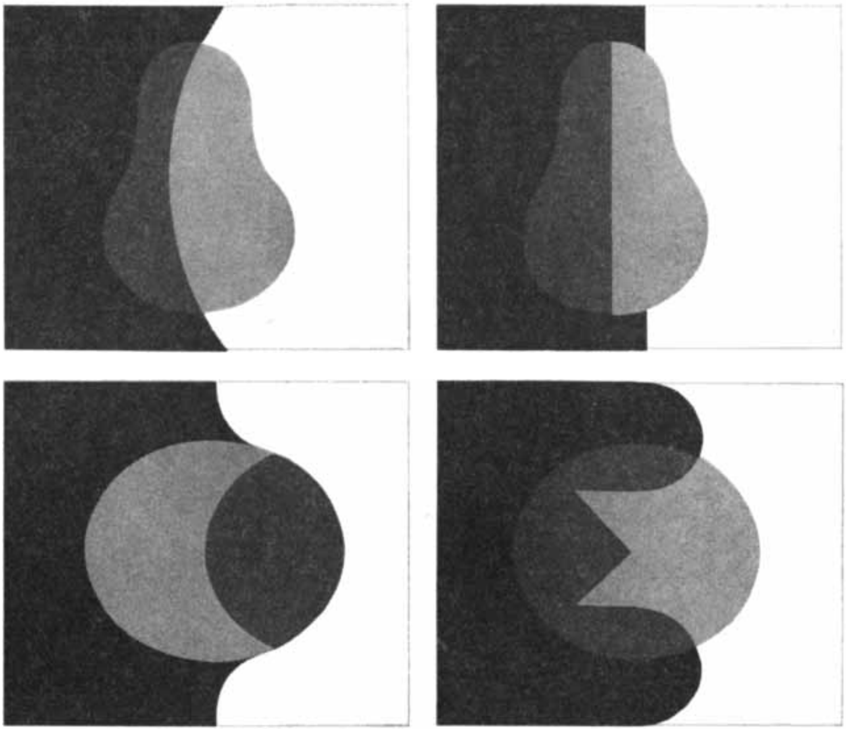
A device for studying color fusion is the color wheel. Two or more colors are placed on the wheel, which is then rotated rapidly. The fusion color perceived depends on two factors: the component colors and the proportions in which they are mixed [*see illustration on opposite page*]. With achromatic colors the resulting fusion color can readily be predicted, but with color scission there is a great variety of ways in which the stimulus color can split. How can we determine how much of the stimulus color will go to the transparent layer and how much to the opaque layer?

Let us consider first the transparent layer. By way of example imagine what happens when you add a dye to a glass of water. As more dye is added the water becomes less transparent and objects seen through the water become less visible. It is therefore plausible that in the scission process the greater the proportion is of color going to the transparent layer, the less its perceived transparency will be.

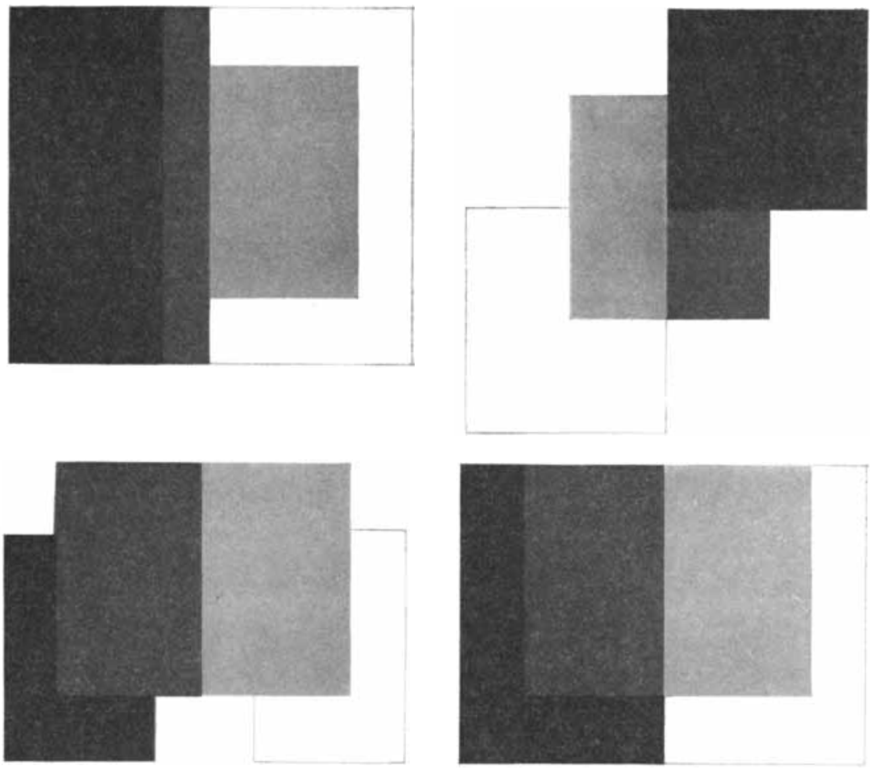
Now let us consider the opaque surface. Suppose that as you view it through a glass of water it is painted with a dye. Obviously the visibility of the opaque surface will increase as more dye is put on it.

The limiting case in the scission process is when all the color goes to one layer. If all the color goes to the transparent layer, it becomes opaque. If all the color goes to the underlying surface, then the transparent layer becomes invisible. Transparency is perceived only when there is a distribution of the stimulus color to both the transparent layer and the opaque layer. Moreover, transparency varies directly with the proportion of color going to the opaque layer. As more color goes to the opaque layer, less goes to the transparent one and the more transparent it appears. The proportion of color going to the opaque layer, which is described by an algebraic formula, can therefore be regarded as an index of transparency.

With achromatic colors it is possible to derive a second algebraic formula that



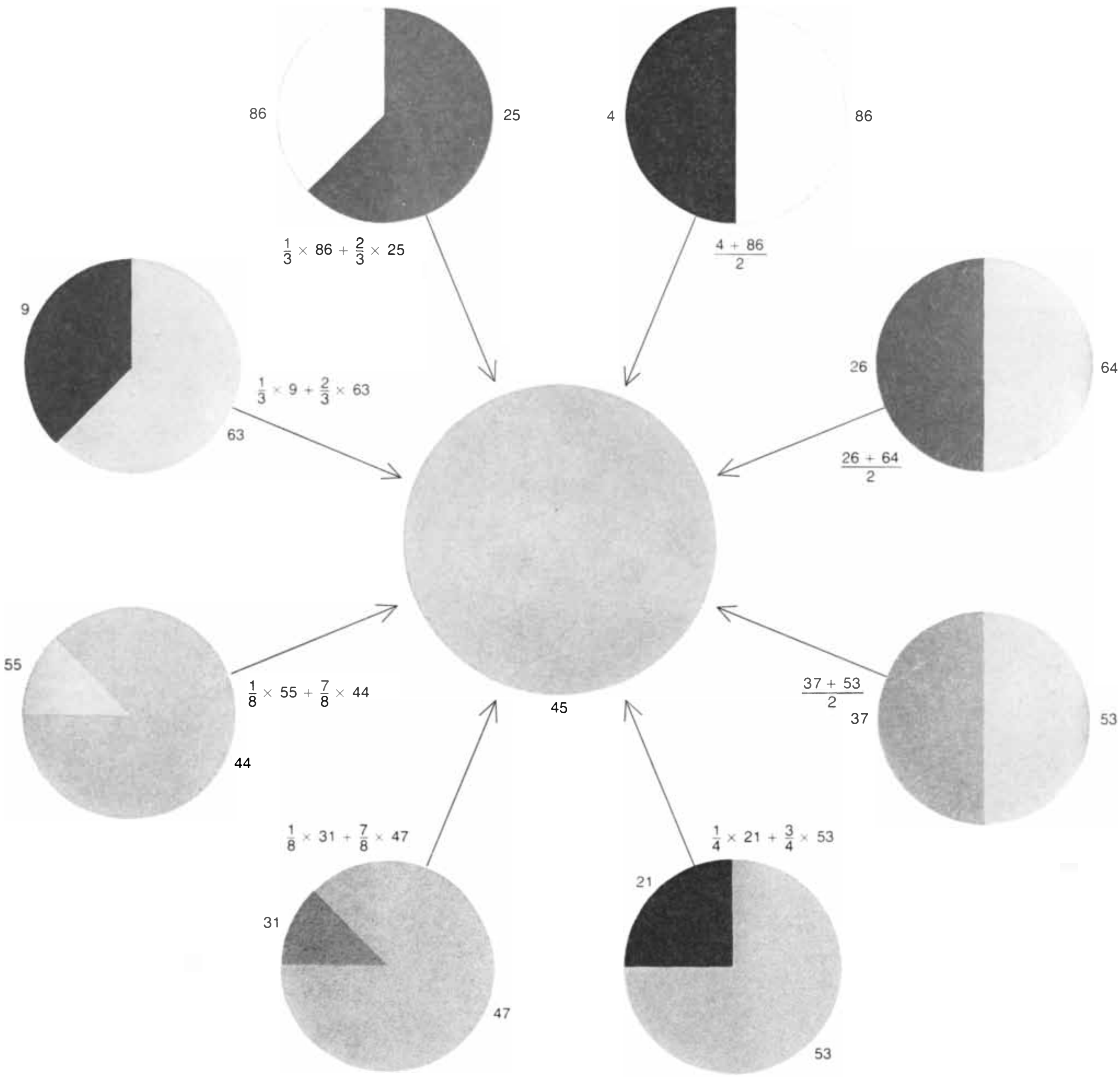
BOUNDARY LINE must appear to belong to the underlying opaque regions and must be visible through the transparent layer for transparency to be perceived (*top left*). Sudden change of the boundary line at the points of intersection causes transparency to be lost (*top right and bottom left*), but in other locations, even in the region that appears to be transparent, it can make abrupt changes without affecting the transparency (*bottom right*).



STRATIFICATION OF SURFACES is another necessary condition for the perception of transparency. If the light gray and the dark gray regions of a figure are perceived as being two different strata, figural unity is lost and transparency is not perceived (*top left*). Another example of inadequate stratification is when the gray regions appear to have an opaque layer above them (*top right*). The underlying opaque regions must meet under the whole of the gray regions in order for transparency effect to occur (*bottom left and right*).

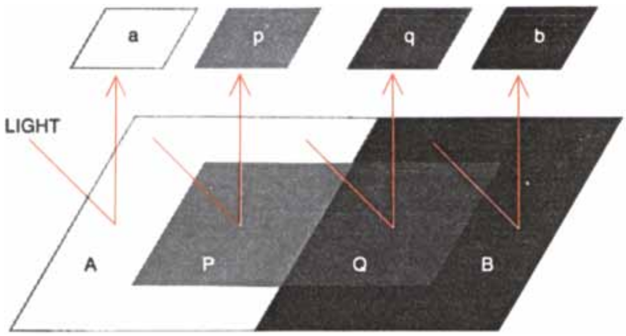
states a relation between the reflectances of the surfaces involved and the color of the transparent layer [*see illustration on next page*]. If the reflectances of the four surfaces in the figure are known, then the index of transparency can be calculated and the relative lightness of the transparent layer can be predicted. Such predictions are possible when (in most cases, as it happens) the transparent layer is perceived to be uniform in color as well as in the degree of transparency; in other words, the transparent layer is a perceptual unit, not divided by the boundary belonging to the opaque layer below.

The validity of the theoretical algebraic formulas can be tested by taking our model figure and altering the color (black, gray and white) of individual regions. When the reflectance values of the gray squares are very different, the calculated coefficient of transparency is large and therefore transparency should be readily perceived. When the gray regions are similar, the coefficient is very small and transparency usually is not perceived. Some necessary color conditions of transparency can be deduced from the theoretical formulas. Transparency is possible only when the darker gray square is on the darker underlying surface and the lighter gray square is on the lighter underlying surface. If these conditions are not met, transparency cannot be perceived. Finally, the difference of reflectance of the colors in the transparent layer must always be less than the difference of reflectance of the



COLOR FUSION is produced when a wheel with sectors of different colors is rapidly rotated. With achromatic colors (black, gray and white) the fusion color can be calculated. For example, if the disk has two sectors of equal size, then the fusion color perceived will be the simple average of the reflectance of each sector. If the sectors are of unequal size, the fusion color is the weighted average. The reflectance figures given here are only representative. The same shade of gray (*center*) can be produced by a variety of color mixtures. Since color scission is the reverse of color fusion, it is apparent that a particular gray can split in a great variety of ways.

1



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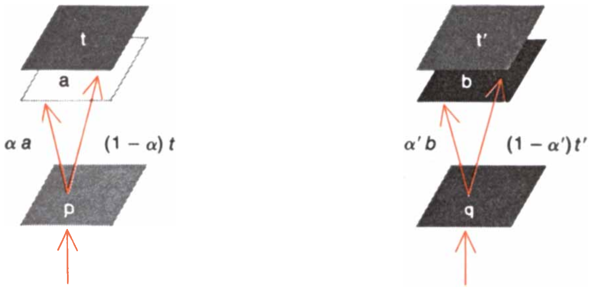
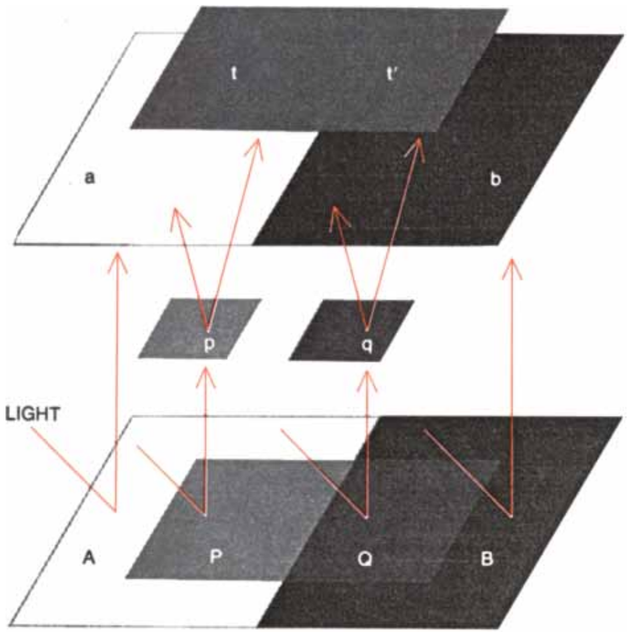


$p = \alpha a + (1 - \alpha) t$ OR $\alpha = \frac{p - t}{a - t}$ $q = \alpha' b + (1 - \alpha') t'$ OR $\alpha' = \frac{q - t'}{b - t'}$

3



IF $t = t'$ AND $\alpha = \alpha'$ THEN $\alpha = \frac{p - t}{a - t} = \frac{q - t}{b - t} = \frac{p - q}{a - b}$, $t = \frac{aq - bp}{(a + q) - (b + p)}$

4

LEFT HALF $\alpha = \frac{p - t}{a - t}$		RIGHT HALF $\alpha = \frac{q - t}{b - t}$
a > p > t	AND	b > q > t
a > p > t	AND	t > q > b
t > p > a	AND	t > q > b
t > p > a	AND	b > q > t

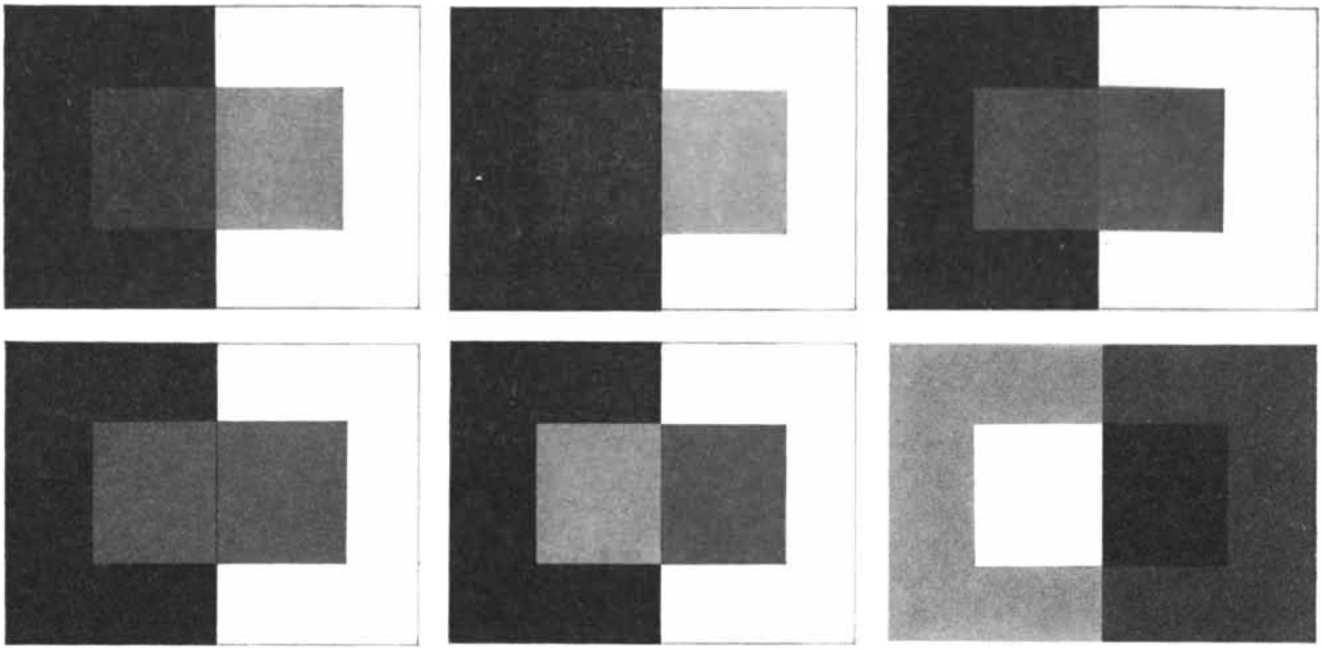
colors in the underlying layers [*see top illustration on page* 98].

Another powerful factor in perceiving transparency (in addition to the proportion of color going to the opaque and the transparent layer) is the color of the transparent layer itself. All other conditions being equal, the darker the transparent layer, the greater its perceived transparency.

The conditions for the perception of transparency that are deduced from the algebraic formula also enable us to predict the degree of lightness of the transparent layer when the colors of the stimulus regions are varied. With our model figure it is not always easy to judge the color of the transparent layer. With a checkerboard pattern, however, such estimations are easier to make and predictions about the transparent layer are visually confirmed [*see bottom illustration on page* 98].

The color conditions for perceptual transparency discussed here are theoretically derived without any empirical correction or adaptation. They state relations for "pure" achromatic conditions. Figural conditions, as has been noted, play a role and cannot be entirely excluded, but they can be held constant. It must be stressed that the inferences drawn from the theory should be considered as describing some (but not all) necessary conditions for the perception of transparency. In other words, certain instances are described where the perception of transparency is possible and instances where it is impossible. Of

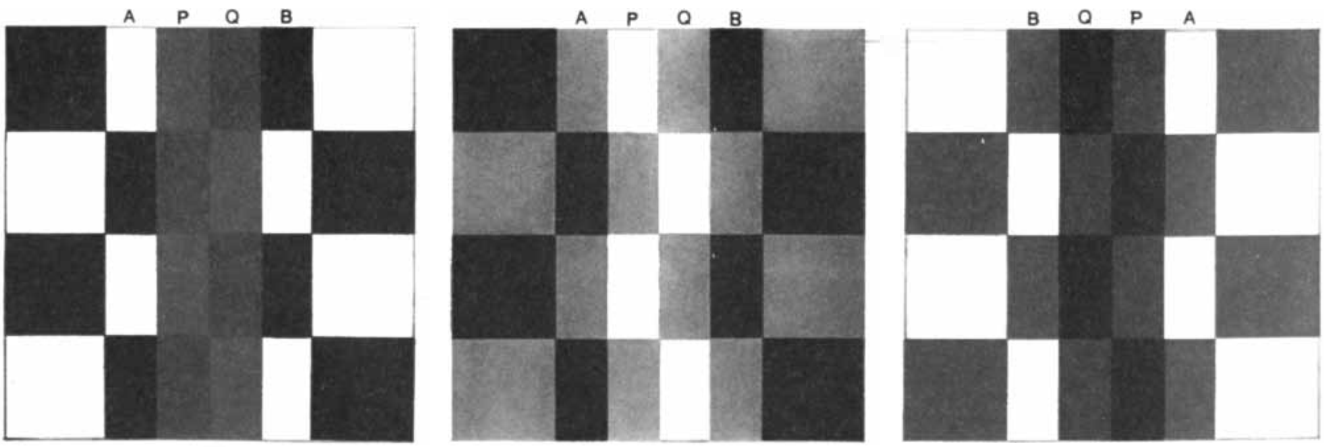
THEORY OF COLOR SCISSION explains transparency as a case of perceptual color-splitting. The achromatic colors can be defined simply by the percentage of light they reflect (*1*). When transparency is perceived, the areas *P* and *Q* split and appear to consist of two surfaces, equal in form and size but different in color. Assuming that this color scission follows the same law as color fusion, then the proportion of the stimulus color going to each of the perceived surfaces can be described by an algebraic formula (*2*). The symbols α and α' stand for the proportion of color (which can vary from zero to one) going to the opaque layers *a* and *b* respectively. The remainder of the color goes to the transparent layers *t* and *t'*. If $\alpha = \alpha'$ and $t = t'$ (*3*), then the algebraic equations can be solved for α (transparency) and for *t* (color of transparent layer). From the formulas certain predictions about the perceived lightness of the transparent layer can be made from the relations of the colors of the *A*, *P*, *Q* and *B* regions (*4*). The symbol > here means "lighter than."



COLOR CONDITIONS necessary for the perception of transparency are demonstrated. In the model figure transparency is readily perceived (*top left*). According to the author's theoretical formula, the degree of perceived transparency increases when the difference between the dark and light gray regions is increased (*top middle*). When the gray regions are similar, perceived transparency is low (*top right*). When the grays are identical, no transparency is perceived (*bottom left*). Transparency is impossible when the darker gray is over the lighter background (*bottom middle*). If the difference between light and dark colors of the background is less than the difference between the colors of the central region, then the central region is not perceived as transparent (*bottom right*).

course, not everyone will perceive transparency when it is theoretically possible. On the other hand, when it is predicted that it is impossible for transparency to exist in a figure, no one should be able to perceive it.

There is an important limitation to the index of transparency that has been discussed: it measures the degree of transparency only if the lightness of the transparent layer is held constant. It is possible to develop a new formula in which the color of the transparent layer is variable, but this can only be done empirically, and it would not give rise to the interesting deductions possible with a theoretical formula. We have dealt here primarily with instances of balanced transparency, that is, instances where the perceived transparent layer is uniform in degree of transparency and color. There are instances of unbalanced transparency, where the perceived transparent layer varies in degree of transparency. A special case is that of partial transparency, where one part of the upper layer is perceived as being transparent and the other as being opaque. Unbalanced transparency and partial transparency, of course, require different formulas for their theoretical description. Other factors such as motion and three-dimensionality are often involved in the phenomenon of transparency. It appears, however, that the main conditions for the perception of transparency are to be found in the figural and chromatic conditions that have been described here.



PERCEIVED LIGHTNESS OF TRANSPARENT LAYER depends on the relation of the colors in the figure and can be deduced from the author's theoretical formulas given in the illustration on page 96. According to his theory, if region *A* is lighter than *P* and region *Q* is lighter than *B*, then the perceived transparent layer appears to be darker than *P* and lighter than *Q* (*left*). If region *P* is lighter than *A* and region *Q* is lighter than *B*, then the transparent layer appears to be lighter than any of the colors (*middle*). If region *A* is lighter than *P* and region *B* is lighter than *Q*, then the transparent layer appears to be darker than any of the colors (*right*).