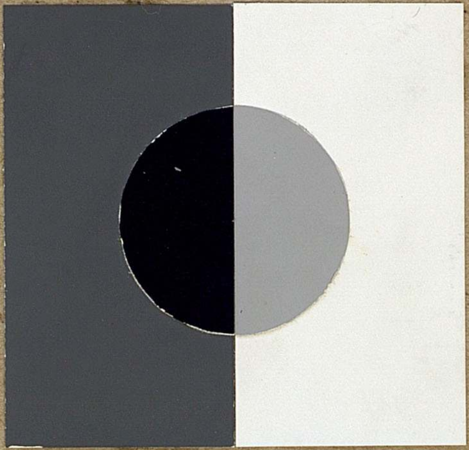

21

Fig. 21

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Fabio Metelli

STIMULATION AND PERCEPTION OF TRANSPARENCY

Summary

After a brief exposition of the algebraic theory of transparency and of the various experimental predictions deduced from it, the theory is reconsidered with reference to the paradigmatic case of transparency obtained using an episcotister. The first result of this analysis is that the same local stimulation, described by the same equation, gives rise either to color fusion or to color scission, that is to transparency. And therefore the assertion that the same equations (Talbot's law) describe both the color fusion and transparency is not an hypothesis but the ascertaining of a fact. Another important result is that the two parameters of transparency, the coefficient of transparency α and the measure of the color <u>t</u> of the transparent layer, correspond to the empty sector of the episcotister and to the color of the episcotister respectively, both being therefore physical measures. being

As the psychological scales respect the order of the physical scales, the deductions from the algebraic expressions of the theory, all consisting in relations of order (> , <) fulfilled the predictions. However this achievement is not reached if the above parameters are used for predicting the perceptual measure of transparency. For this purpose another couple of equations have been deduced apparently equal to the equations using physical measures, but where <u>perceptual</u> measures of the independent variables (the colors of display) are used, which allow us to calculate the dependent variables α^* (coefficient of <u>perceived</u> transparency) and t^* (the perceived color of the transparent layer).

Riassunto

Dopo un'esposizione sommaria della teoria algebrica della trasoarenza e delle varie previsioni sperimentalmente controllabili dedotte dalle equazioni della trasparenza, la teoria viene esaminata alla luce del caso paradigmatico della trasparenza ottenuta per mezzo dell'episcotista.

Il primo risultato di questa analisi è che la stessa stimolazione locale, descritta dalla stessa equazione, dà luogo o alla fusione cromatica o alla scissione cromatica, cioè alla trasparenza. Perciò l'asserzione che le stesse equazioni descrivono sia la fusione cromatica (Legge di Talbot) sia il processo inverso, cioè la trasparenza, non è un'ipotesi ma la constatazione di un fatto.

Un altro importante risultato di questa analisi è che i due parametri della trasparenza, il coefficiente di trasparenza α e la misura del colore dello strato trasparente $\underline{t}$ corrispondono, il primo al settore vuoto dell'episcotista e il secondo alla riflettanza dell'episcotista e consistono quindi in misure fisiche.

Poiché le scale psicologiche rispettano l'ordine delle corrispondenti scale fisiche, le deduzioni dalle espressioni algebriche, consistenti tutte in relazioni di ordine ($>$, $<$) corrispondono alle previsioni. Non si ha invece tale corrispondenza se i parametri suddetti sono usati per prevedere la misura percettiva della trasparenza.

A tale scopo viene dedotta un'altra coppia di equazioni a due incognite, che risultano apparentemente uguali alle equazioni che usano le misure fisiche, ma che invece al posto delle misure fisiche usano le corrispondenti misure percettive e consentono di calcolare le variabili dipendenti α^* (che misura la trasparenza <u>percepita</u>) e $\underline{t}^*$ (che misura la chiarezza <u>percepita</u> dello strato trasparente).

1. *Transparency as a chromatic scission*

In some previous papers (Metelli, 1974a, 1974b) I showed that physical transparency is neither a necessary nor a sufficient condition for the perception of transparency, and that the perception of transparency depends on figural as well as chromatic conditions. Here the chromatic conditions of transparency are discussed, beginning with a summary of the theory and its experimental confirmations.

The starting point of the theory is G.M. Heider's (1933) interpretation, (see also Koffka 1935, pp. 260-264) of transparency as a chromatic scission. It is a case of phenomenal splitting, namely a process where one stimulation gives rise to two perceptual data, as in the classic case of the perception of color and illumination. In the case of transparency, we perceive, as an effect of a single stimulation (a mixture of different wave-lengths), not a single color, but two colors, two colored surfaces, one seen through the other. From G.M. Heider's experiments it appears that when the colors of the two layers, one transparent and one seen through transparency, are fused together, they yield what I called the stimulus-color; i.e. the color perceived in place of the transparent region, when an opaque surface is perceived instead of transparency.[1]

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[1] This case also occurs if the necessary figural conditions (see Metelli (1967) and Kanizsa (1980)) for transparency are present (Fig. 1), but as a rule it occurs when the aforesaid figural conditions are lacking (Fig. 2). G.M. Heider's experiment was done using chromatic colors (blue and yellow, yielding gray as a fusion color) but, as appears in the following section, for the sake of simplicity the present theory has been deduced with reference to achromatic colors. For an extension of the theory to chromatic colors, see Da Pos (1976) and a critical paper by Beck (1978).

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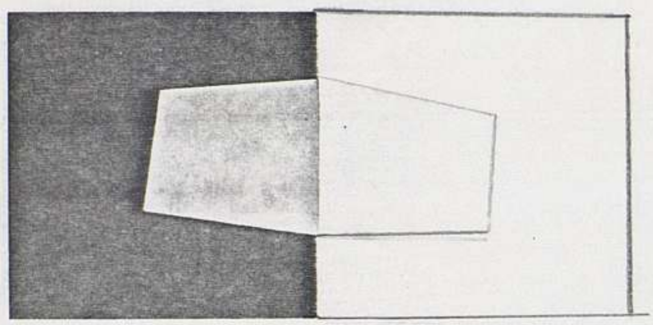

FIG. 1. A transparent gray layer through which a part of the A and B regions are seen is generally perceived (Figural conditions for transparency present).

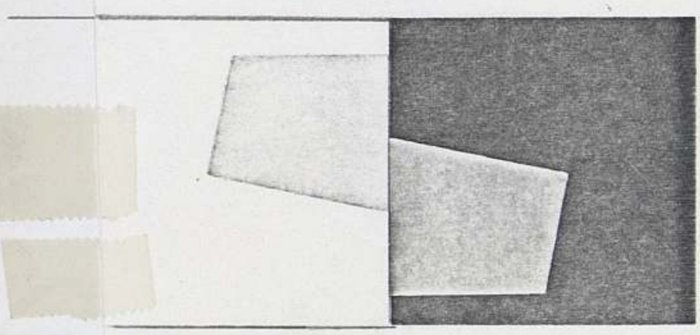

FIG. 2. Two opaque gray figures laying on a bicolor ground are perceived (Figural conditions for transparency lacking).

2. *Deduction of the transparency equations*

In the special case of achromatic colors, Talbot's law states that the reflectance of a fusion color is the weighted average of the reflectances of its component colors, the weights being proportions of the colors mixed together.

In the case of fusion of two achromatic colors, Talbot's law can be expressed by the following equation transparency for the left half of the figure by equation

$$(1) \quad p = \alpha a + (1-\alpha)t$$

The use of this and the following equation to express quantitatively the phenomenon of transparency is justified by the following considerations.

As has been said before, the phenomenon of transparency is a perceptual scission. In region P (Fig. 3) we see a transparent surface T, and through it an opaque surface A.

Schematically $$P \begin{matrix} \nearrow & T \\ \searrow & A \end{matrix}$$

Let us take it as proved (see Moore Heider, 1933) that color <u>t</u> of surface T and color <u>a</u> of surface A, when taken in a certain proportion and fused together, again yield color <u>p</u> of the P region

Schematically $$\begin{matrix} t & \searrow \\ a & \nearrow \end{matrix} P$$

Talbot's law predicts what will be the fusion color <u>p</u>, starting from the component colors and their quantity; that is, in the case of achromatic colors

$$\alpha a + (1-\alpha)t = p$$

(where α and $(1-\alpha)$ are the proportions of the two colors in the mixture, and <u>a</u> and <u>p</u> are the reflectances of the A and P surfaces).

Then Talbot's equation, read from right to left, expresses the phenomenon of transparency quantitatively

$$p = \alpha a + (1-\alpha)t$$

i.e., transparency as a color-scission is <u>quantitatively</u>

the inverse process of color mixture (scission colors, when mixed together, yeld the color which splits),

Schematically
$$\begin{tikzcd} & t \arrow[dl, shift left] \\ p \arrow[ur, shift left] \arrow[dr, shift left] & \\ & a \arrow[ul, shift left] \end{tikzcd}$$

For the right half of figure 3, chromatic scission is described by equation

$$(2) \qquad q = \alpha' b + (1-\alpha')t'$$

Namely color p, which we perceive isolating region P, and whose reflectance can be measured with a photometer, splits into an upper layer T with a reflectance t and a lower layer A, which is perceived as a part of region A, whose reflectance is a. The same happens to color q of region Q, which splits into an upper layer T whose reflectance is t' and in a lower layer B which is perceived as a part of region B, whose reflectance is b.

In equation (1) we have two known terms, p and a, and two unknowns, α and t; in equation (2), there are also two knowns, q and b, and two unknowns, α' and t'. If the unknowns of the two equations are the same, that is if $\alpha = \alpha'$ and $t = t'$, we can solve the system of two equations with two unknonws, obtaining

$$(3) \quad \alpha = \frac{p-q}{a-b} \; (a \neq b) \qquad \text{and} \qquad (4) \quad t = \frac{aq - bp}{(a+q)-(b+p)} \; (\alpha \neq 1)$$

The meaning of α and t needs to be clarified. The meaning of t is easily explained: it is the virtual reflectance[2] of the transparent layer T. Therefore, if the color of the transparent layer is equal in both regions P and Q, the condition $t = t'$, necessary for deducing equations (3) and (4) is satisfied.

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[2] see Masin & Cavedon (1978).

α and $(1-\alpha)$ are the weight coefficients, that indicate the quantity of color going into each of the two layers A and T for the P region and to the two layers B and T for the Q region. A very enlightening interpretation of the α coefficient is suggested by a consideration of the two extreme cases, where one of the two layers receives all the color, and the other no color at all, that is giving to α in both equations (1) and (2), first the value 0 and then the value 1.

If $\alpha = 0$, equation (1) reduces itself to $p = t$, and equation (2) to $q = t$, and therefore equation (3) to $p = q$; that is $p = q = t$. But if $p = q$, the color of the P and the Q regions being the same, we have a homogeneously colored circle (Fig. 4), which is perceived as opaque. In other words, if $\alpha = 0$, there is no transparency (Fig. 4).

itself

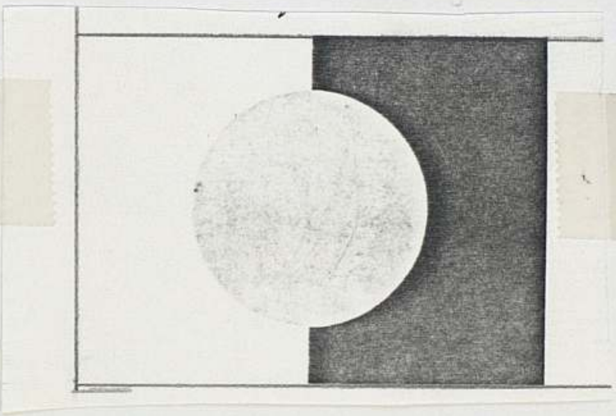

FIG. 4.

mettere in mezzo fig 4

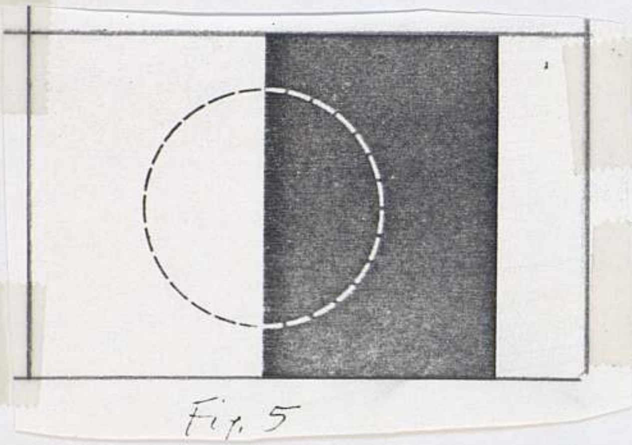

FIG. 5. ...... virtual boundary of the perfectly transparent region

If $\alpha = 1$, equation (1) yields $t = a$ and equation (2) $t = b$; this means that instead of seeing a transparent layer, and regions A and B through it, we see only the A and B regions and nothing over them; in other words transparency is perfect and the transparent layer is invisible (Fig. 5). Summarizing, $\alpha = 0$ predicts no transparency (opacity), while $\alpha = 1$ predicts perfect transparency. Thus α can be taken as a coefficient of transparency [3]. Therefore the condition justifying the deduction of formulas (3) and (4) is, $t = t'$ (equality of color of the transparent layer in the P and Q regions, which seems to be almost generally present) as well as $\alpha = \alpha'$, that is, transparency (measured by α) has to be equal in the two halves of the paradigmatic figure 3 (balanced transparency).

---

[3] Another condition affecting transparency appears to be the reflectance of the transparent layer. All other conditions being equal, including α, the less the reflectance of the transparent layer, the greater the degree of transparency we perceive (See Tudor Hart, 1922).

3. *Testing the validity of the theory*

An especially satisfactory procedure for testing the validity of the equations deduced algebraically consists in inferring empirically testable conditions from the equations. This procedure is also a way of testing the theory of transparency as perceptual scission, a process similar in nature to chromatic fusion and therefore ruled by Talbot's law. The following testable predictions were inferred (Metelli, 1970, 1974, 1975, 1978; Masin and Cavedon, 1980):

1. $\underline{\alpha < 1}$. For values of α greater than 1, $(1-\alpha)$ would acquire a negative value, and therefore the transparent layer would have a negative quantity of color, which is devoid of meaning. Therefore when transparency is perceived, α must be less than 1.

From equation (3) we see that if $\alpha < 1$, $/p-q/ < /a-b/$, i.e. the difference in lightness [4] between the splitting regions P and Q must be less than the difference in lightness between regions A and B. In Fig. 3 this condition is satisfied.

If, in order to test the above necessary condition of transparency, we substitute reflectance $\underline{a}$ with $\underline{p}$ and $\underline{b}$ with $\underline{q}$ [5], a strange result is obtained; instead of P and Q, A and

---

[4] As will be explained later in Section 6, the order of perceptual impressions corresponds to the order of physical measures. In this and in the following cases we are justified in using the concept of lightness (subjective measure, or impression) instead of reflectance (physical measure), and therefore rely on our impressions, when looking at the figures.

[5] That is, we construct a figure 3b, like figure 3, but use a gray of reflectance $\underline{p}$ for the region A, a gray of reflectance $\underline{a}$ for the region P, a gray of reflectance $\underline{b}$ for the region Q, and a gray of reflectance $\underline{q}$ for the region B. The result of this operation is that in the new figure, regions P and Q show a greater difference in lightness than regions A and B.

B are seen splitting, that is the regions being less different in lightness become transparent [6], assuming that they take on the functions of P and Q. So the necessary condition $\alpha < 1$ is confirmed (see Fig. 3b, 6, 6a).

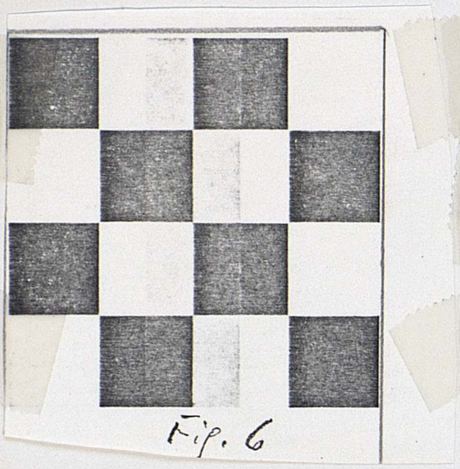

FIG. 6.

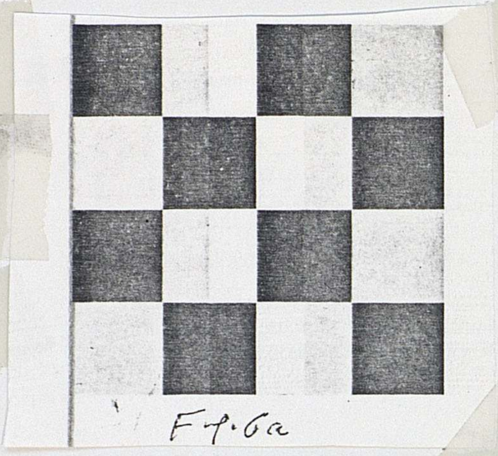

FIG. 6a.

2. $\underline{\alpha > 0}$. For analogous reasons the values of $\alpha < 0$ are excluded since region A according to equation (1) and region B according to equation (2) would receive a negative quantity of color. Therefore if $\underline{a} > \underline{b}$, necessarily $\underline{p} > \underline{q}$ (if $\underline{a}$ is

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[6] The effect is much more evident in Fig. 6 and 6a, which are constructed according to the same rules as Fig. 3 and 3b. In fact, Fig. 6 and 8-13 are alternations of sequences BAPQBA and ABQPAB. The sequences giving rise to transparency are APQB (as in Fig. 3) and its inverse BQPA. Squares A and B were added at the beginning and end of each sequence in order to make the organization giving rise to transparency more stable.

lighter [7] than <u>b</u>, <u>p</u> must be lighter than <u>q</u>), and if $a < b$, necessarily $p < q$; otherwise α becomes negative. In Fig. 3 the condition is satisfied and observers perceive transparency; in Fig. 7 the colors of <u>p</u> and <u>q</u> are inverted and we have $a > b$ and $p < q$. In this case nobody perceives transparency. If we define $a > b$, that is, we call A the lighter of the two non-splitting regions, the necessary condition becomes $p > q$.

3. <u>α = coefficient of transparency</u>. Considering $\alpha = \frac{p-q}{a-b}$ we see that if (a-b) is much larger than (p-q), than α is large and trasparency is great. If (a-b) is kept constant, transparency grows as (p-q) increases (See Fig. 8 and 9, confirming the above prediction).

4. <u>If $\alpha = 1$, t = 0/0</u>. If $\alpha = 1$, p-q = a-b, and using this deduction in (4), <u>t</u> becomes 0/0. The above formulation means that in the case of perfect transparency (α=1) the color of thr transparent layer is indefinite (t = 0/0). [8]

However it coud be objected that what is perfectly transparent is not visible and can have no color. Masin and Cavedon (1980), starting from the above statement, tested a hypothesis of a continuity from $\alpha = 0$ to $\alpha = 1$, i.e. the greater αs, the narrower the range of perceived lightness of the transparent layers. The results of their experiments

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[7] For the reasons given in fn. 4, p. 10 we are justified in interpreting the symbol > as "lighter" as well as "having greater reflectance".

[8] It should be remembered that since <u>t</u> is measured in terms of reflectance, t=0 does not mean "no color, but black.

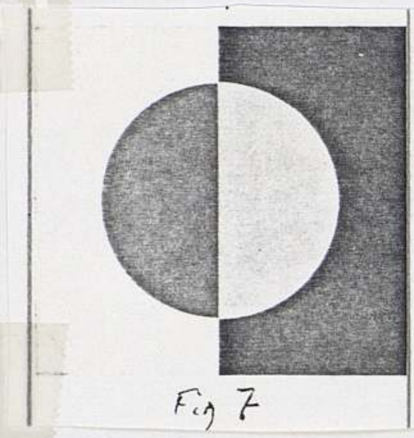
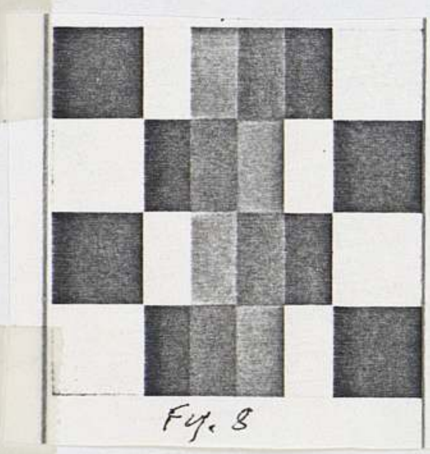


FIG. 7.



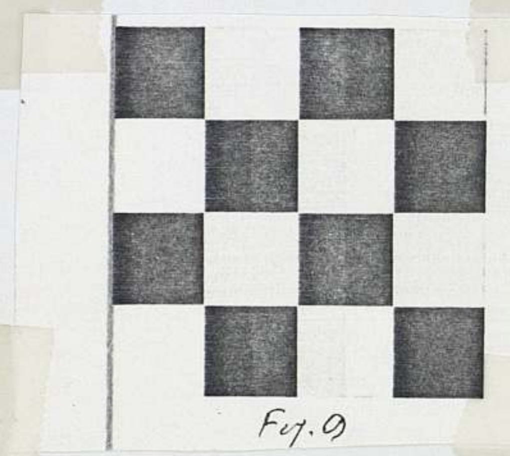


FIG. 8. Little transparency.   *FIG. 9. high transparency*

confirmed the hypothesis.

5. $\underline{(a > p), (b > q) \Longrightarrow t < a,b,p,q}$ [9]. If the A region is

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[9] The deduction of formulation 5, 6 and 7 can be found in Metelli (1974a and 1975).

lighter than the P region, and the B region is lighter than the Q region, then the transparent layer T is darker than each one of the above four regions.

As a test of this formulation, see Fig. 10 and 11 [10].

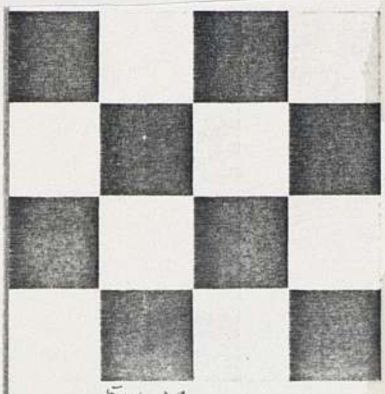

FIG. 10. $a > p > b > q$
(transparent layer dark)

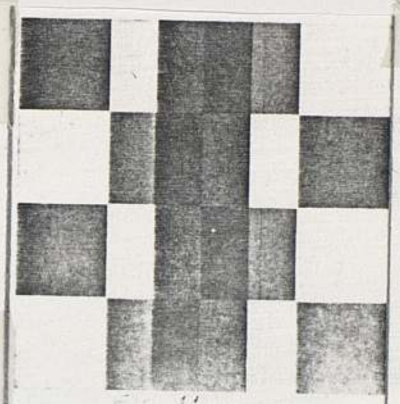

FIG. 11. $a > b > p > q$
(transparent layer dark)

6. <u>$(a > p), (p > q), (q > b) \Longrightarrow p > t > q$.</u> If region A is lighter than P, P is lighter than Q and Q is lighter than B, the transparent layer T is lighter than Q and darker than P, or, in other words, T is an intermediate gray between P and q. As a test of this formulation see Fig. 3 and 6.

7. <u>$(p > a), (q > b) \Longrightarrow t > a,b,p,q$.</u> If region P is lighter than region A, and region Q is lighter than region B, the transparent layer T is lighter than each one of the above four regions. As a test of this formulation see Fig. 12 and

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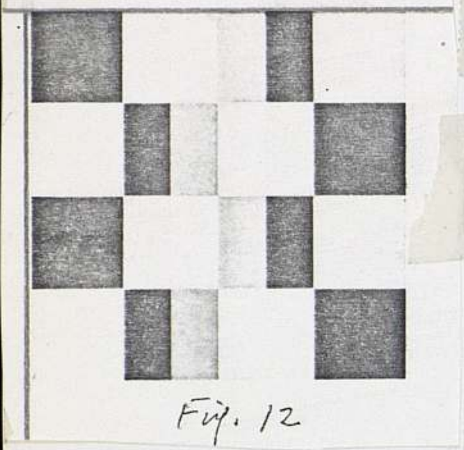
[10] As the degree of transparency in Fig. 10 is very high, the darkness of the transparent layer may not appear evident.

13 [11].

Than all the above formulations deduced from equations (3) and (4) were supported by experimental tests.



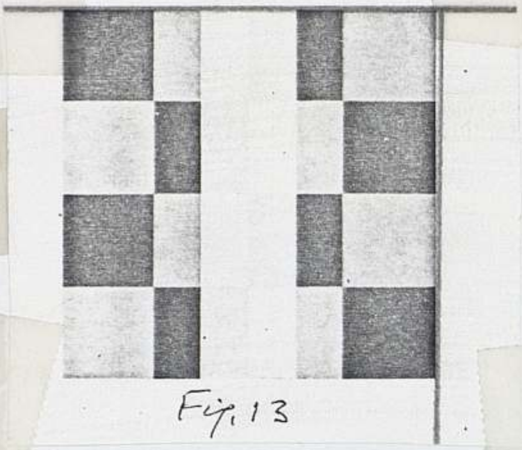


FIG. 12. p > a > q > b
(transparent layer light)

FIG. 13. p > q > a > b
(transparent layer light)

The chromatic theory of transparency was first published in 1970 and further research has been done in the last decade (see Argenton and Zambelli (1976), Da Pos (1976a,b, 1977), D'Urso (1975), Gerbino (1975), Gyulai (1976), Gyulai and Metelli (1976), Lis (1976, 1977), Masin (1978a,b, 1979, 1980), Masin and Metelli (1979), Metelli (1975b, 1976), Remondino (1976). The present paper is intended to investigate further into the meaning of the parameters of perceptual transparency, t and α and to attempt a way of deducing the theory and its basic equations, not just from a conception of transparency

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[11] Figs. 12 and 13 (like Figs. 10 and 11) differ in the degree of transparency.

as a perceptual splitting as being the inverse of color fusion, but from experimental conditions where the phenomenon can be studied [12].

4. *Critical examination of the theory of transparency: chromatic fusion and scission with an episcotister.*

A interesting technique for examining the theory of transparency is founded on the use of the episcotister, i.e. a circular sector [13] (or a disk with a sector cut out) which rotates at fusion speed [14].

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[12] The project of investigating this topic further originated from a result obtained by Professor Jacob Beck of the University of Oregon. He asked his subjects to give an estimation of the degree of transparency of some figures, but the average results were quite a long way from the calculated αs.

Beck's results are based on a limited number of observations; however they put the quantitative theory of transparency into difficulty. Beck also observed that if subjective data were substituted for the measures of reflectance in the α formula, the predicted degree of transparency was very close to that estimated (see Appendix).

[13] For technical reasons the episcotister is made of two sectors opposite the vertex (Fig. 14). But to simplify the discussion it is more convenient to speak of one sector (Fig. 14a).

[14] By fusion speed I mean the speed that gives rise to the perception of a steady disk when a Maxwell disk (Fig. 15), of the same colors as the episcotister and the ground, taken in the same proportions, rotates.

disk is perceived (Fig. 16a) where color p can be calculated from the reflectance of surface t of the episcotister, from reflectance a of the ground behind it, and from size α of the episcotister's cut out sector [15]. In fact, reflectance of the fusion color is, according to Talbot's law, a weighted average of the reflectances of its component colors, the weights being the proportions in which the colors are present in the mixture. As the component colors are two, the same equation (2) considered above

$\alpha a + (1-\alpha)b = c$ or, in our case $\alpha a + (1-\alpha)t = p$

describes the phenomenon.

Indeed α and $(1-\alpha)$ are proportions in which the ground and the episcotister stimulate the eye of the observer (1 being the unity of time considered): the greater the cut out sector of the episcotister, the greater α with respect to $(1-\alpha)$, and the longer the time the eye is stimulated by the ground a compared with the time it is stimulated by the episcotister t. The equation (1) states the proportion in which each of the two stimuli a and t acts [16].

---

[15] One should remember that the colors considered in this paper are achromatic (of the series black-gray-white).

[16] As a matter of fact stimulation by an episcotister and ground, i.e. by the circular region where the ground is periodically covered by the rotating episcotister is exactly the same as stimulation using a Maxwell disk where color a of ground is present as a sector equal to the lacking sector α of the episcotister and color t of the episcotister by a sector equal to the episcotister $(1-\alpha)$.

It is well known that if, instead of homogeneous, the surface behind the episcotister is such that it gives rise to the perception of one or more figures on a ground (Fig. 17) or, in the simplest case, consists of two contiguous achromatic surfaces differing in reflectance (Fig. 18), chromatic fusion does not take place, but a transparent disk is perceived, through which the figures or surfaces covered by the transparent disk are seen.

Perception is quite different, but local stimulation is the same [17]; however the surfaces partly covered by the rotating episcotister must to be at least two in order to perceive transparency [18]. But in the simplest case (ground

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[17] Stimulation originated by the P region is exactly the same, in Fig. 16 (homogeneous ground) and Fig. 18 (bicolor ground). For example, if the episcotister is a sector of 90° and there are 2 regions, A (a) and B (b), every point of the retinal region corresponding to surface A, which is periodically covered by the episcotister, is stimulated for 1/4 of the time by color t of the episcotister and 3/4 of the time by color a of the ground. The same thing happens with surface B.

[18] Since is the simplest case for obtaining transparency, we shall use Fig. 18 as a paradigm, where the ground consists of two parts with different reflectances, A (a) and B (b).

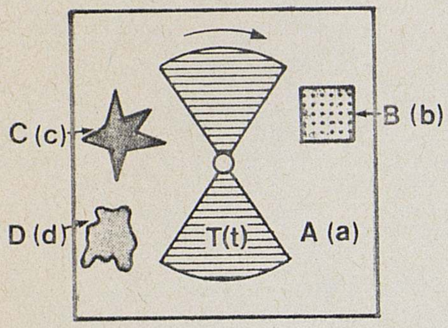

FIG. 17.
T(t) episcotister
A(a) ground
B(b) C(c), D(d) figures
with different reflectance

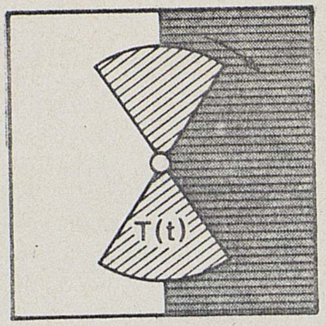

FIG. 18.
T(t) episcotister

divided into two regions of different reflectance) the equations describing the alternate stimulation due to episcotister and ground become two. One equation relates to the P region, corresponding to the retinal projection of the A region periodically covered by the episcotister, and the other relates to the Q region, corresponding to the retinal projection of the B region periodically covered by the episcotister (see Fig. 19).

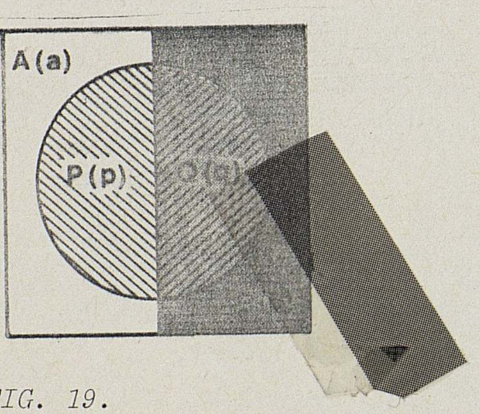

FIG. 19.
A,P,Q,B = regions
a,p,q,b = reflectances

In other words, the situation can be described as follows:

a) Distal stimulation: episcotister with reflectance t, rotating in front of a bicolor surface, whose reflectances are respectively a and b.

b) Proximal stimulation (at the retinal level): four regions A,P,Q,B, whose stimulations are respectively a', p', q', b' (proportional to the reflectances a,p,q,b).

c) Perception: a transparent disk, through which two portions of the A and B regions are visible.

The equations

$$p = \alpha a + (1-\alpha)t$$
$$q = \alpha b + (1-\alpha)t$$

are the same as equations (1) and (2), which have been deduced from the hypothesis that chromatic scission (i.e. transparency) can be described by the same equation as chromatic fusion, being the inverse phenomenon (see section 2). But with the episcotister, no hypothesis is necessary, because the equations objectively, describe the stimulation which is locally the same, whether chromatic fusion or transparency is perceived.

It is possible to show directly that the same local[19] stimulation, described by equations (1) or (2), gives rise either to color fusion (predicted by Talbot's law) or to transparency. If we cover (or rather hide) the right half of the display, with a screen of the same color as ground A (see Fig. 20), we perceive an opaque half circle, the color of which results from fusion between the colors of episcotister and ground.

In this case, the fusion color is p and can be calculated by equation (1); if the left half of the display (the

[19] i.e. stimulation corresponding to the region where fusion or scission takes place.

A region) is hidden by a screen of the same color as the B region, the fusion color is q and can be calculated by equation (2). If the screen is removed a transparent disk in front of surfaces A and B is perceived.

Local stimulations in region A are identical when fusion and transparency are perceived; they are therefore described by the same equation in both cases.

With the episcotister the two equations (1) and (2) allow us to calculate the stimulations generated by the P and Q regions in terms of reflectance, independently of each other, i.e., the reflectances of the two achromatic colors p and q which give rise to two stimulations identical to the complex stimulations caused by the P and Q regions of the display (ground + episcotister). In fact, if instead of using the episcotister, we glue two semicircles whose reflectances are respectively p and q (Fig. 3), to the A and B surfaces at the places corresponding to the P and Q regions, a transparent circle partially covering the A and B surfaces is generally perceived [20].

Hence we see a transparent disk not because there is an episcotister periodically covering a circular portion of the surfaces behind it, but what we are perceving depends only on

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[20] Although a', p', q', b' stimulations can be identical as wavelenghth and intensity in the two situations, there is however a difference: with the episcotister a) the transparent disk is not attached to the ground but localized at a certain distance in front of it, and b) its borders are less sharp, a condition that modifies the mode of appearance of the color (Kanizsa 1954). However the similarity of the two situations can be increased in these respects also.

particularly the α and $\underline{t}$ symbols if transparency is obtained when the $\underline{p}$ and $\underline{q}$ stimulations are produced without an episcotister, as occurs in Fig. 3.

The answer is that independently of the diversities stressed in the previous note (n.20 pag.22), the result is the same and therefore the laws of the phenomenon produced by the episcotister are also valid when stimulation is obtained under different conditions. In other words, the necessary conditions for perception of transparency are properties of proximal stimulation [22].

What changes in the two different situations are the unknowns. With the episcotister α and $\underline{t}$ are two data, namely amplitude of the empty sector of the episcotister and reflectance of the episcotister's surface; the reflectances of the fusion colors $\underline{p}$ and $\underline{q}$ are unknown. These can be calculated independently (see diagram 1) $\underline{p}$ by equation (1) and $\underline{q}$ by equation (2). On the other hand, when transparency is obtained by juxtaposition of opaque surfaces (Fig. 3), the $\underline{a}$, $\underline{p}$, $\underline{q}$, $\underline{b}$ reflectances are given (or can be chosen at will), while α, the degree of transparency (if any) in terms of stimulation and $\underline{t}$ (i.e. the possible color in terms of reflectance of the transparent layer) functions of $\underline{a}$, $\underline{p}$, $\underline{q}$, $\underline{b}$ corresponding to the amplitude of the empty sector of the episcotister and to the reflectance of its surface are the unknowns, which we are interested in predicting. (See diagram 2).

The main result of this analysis is that we have been able to show, directly, the adequacy and meaning of equations (1) and (2) in describing the stimulation that gives rise to transparency, without resorting to the hypothesis that transparency is the inverse process of chromatic fusion. In fact, the same stimulation, described by the same equation, gives rise either to color scission, that is transparency, or to

[22] That is stimulation at the retinal level, independently of the empirical conditions giving rise to it.

color fusion [23].

A further advantage of considering transparency with an episcotister is to clarify the problem of the "quantity" of color (α, $(1-\alpha)$), that is distributed in the two layers, a quantity, which must be distinguished from the "quality" ($\underline{a}$, $\underline{b}$, $\underline{p}$, $\underline{q}$, $\underline{t}$) but has to be considered together with the quality (so, for example: (α a)) in the computation of the colors of the two layers in transparency.

Obviously the quality is expressed by the measures of the two colors of the transparent layer and of the ground behind it, which, with achromatic colors, correspond to reflectance, and with an episcotister to the colors (reflectances) of the episcotister and of the ground.

The quantity is clearly defined when transparency is obtained with an episcotister: it is determined by the size of the episcotister sectors. If for example the episcotister sectors sum up to 90°, 1/4 of the stimulations will contribute to build the transparent layer, because only for 1/4 of the time the retinal cells will be stimulated by the rays reflected from the episcotister surface. The quantity of stimulation is expressed by the coefficient (α, $(1-\alpha)$) that indicates how much one or the other of the two colors contributes to the fusion color, which measures the total local stimulation. Perceptually, when transparency is perceived, the quantity of stimulation has its counterpart in the density [24] $(1-\alpha)$ of the transparent layer, and intensity (α) of what is seen throught it.

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[23] Of course, here we are discussing the stimulation giving rise to the scission process. The very process of the perception of transparency will be discussed in the later sections.

[24] The density or opacity of the transparent layer, which is measured by $(1-\alpha)$.

A final advantage is a more precise knowledge of the meaning of the coefficient of transparency, α.

5. *Stimulation and perception of transparency*.

Now we can exploit the possibility of deepening our analysis by referring to the situation of the episcotister as a paradigm of the complex stimulation giving rise to transparency.

But first of all one point must be stressed. As appears without doubt from our preceding analysis, the two equations specify the stimulation originating from the P and Q regions. It has always been clear that the variables a, p, q, b in the equations are measures of stimuli. Besides, t had been always considered a measure of the reflectance of the transparent layer. It was clear from the beginning that it is not a measure of the impression of lightness of the transparent layer but a physical measure of the proportion of light reflected by a gray surface of equal lightness as the transparent layer. Now it is clear that α is not a measure of the impression of transparency of the transparent layer, but of the physical transparency of a filter - the episcotister - giving rise to the same impression of transparency [25]. In Fig. 3, where there is not an episcotister, but a surface with four regions of different reflectance, we can use the system of equations (1) and (2) to calculate the coefficients α and t. What we obtain are the functions of a, p, q, b measuring the stimulation corresponding to the transparency of the filter and the reflectance of its surface which would give rise to the perception of the color of the transparent layer.

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[25] In the equations (1) and (2) stimulation originating from the P and Q surfaces is analyzed in a quantity giving rise to the perception of ground A and B respectively, and a quantity giving rise to the perception of the transparent layer T.

Now let us go back to the situation of the episcotister, where <u>t</u> is the reflectance of the episcotister and α the proportion of its empty sector.

In fact, by systematically varying the conditions in experimenting with the episcotister, we can establish the relations between the components of the stimulation and the aspects of the phenomenon.

First of all we can establish experimentally the relation between the perceived color of the transparent layer and the reflectance of the episcotister: the first has to be estimated by observers, while the second can be measured physically [26].
However until we have precise data, a simple observation justifies the assertion that the lightness of the transparent layer is a direct function of the reflectance of the episcotister: the greater the reflectance of the episcotister, the lighter the (achromatic) color of the transparent layer. It is equally justified - until we have sufficient experimental information [27] - to assert, on the basis of observations, that the density [28] of the transparent layer is a direct function of the size of the episcotister; or, inversely, that the degree of transparency of the nearer layer, and of

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[26] There is, however, a problem if the lightness of the episcotister is the same as the lightness of the transparent layer (see Masin and Cavedon, 1978).

[27] Some experimental data about this relation appear in the paper by Masin, Cavedon and Bressan (1980).

[28] By <u>density</u> we mean the quality corresponding to the physical measure $\beta = 1-\alpha$, which increases when transparency decreases.

visibility of the farther layer through the transparent one, are a direct function of the size of the empty sector α of the episcotister.

It is, evidently, in both cases the function connecting a scale of physical measures with the corresponding scale of subjective measures.

In the case of the lightness t^x of the transparent layer and its reflectance t, the relation is well known. The same (perceived) difference of lightness corresponds to a small difference in reflectance in the region of the dark grays, and to a large difference in reflectance in the region of the light grays [29].

These are trivial notions and equally well known is the fact that, starting from a physical scale of stimuli it is possible to construct, experimentally, a scale of the corresponding impressions, i.e. a psychological scale. But without raising the technical problem of choosing the method and of the different results obtained by different methods, one point, essential for our analysis, has to be stressed: the psychological scale, i.e. of the perceptual impressions is, whatever the method used to measure them, a growing function of the corresponding physical measures: one scale respects the order of the other [30].

In other words, stimulation conditions being constant, for supraliminal differences, if stimuli $r_1 > r_2$, then the

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[29] A classic demonstration can be given with a color mixer which allows variation of the amplitude of sectors during rotation. Using a black and white Maxwell disk and gradually increasing the white sector from 5° to 355° the mixture colour initially increases rapidly in lightness, which grows with negative acceleration. The change becomes almost imperceptible when the mixture is very light.

[30] Of course the statement is valid for the supraliminal differences, which we are presently interested in.

corresponding impressions $e_1 > e_2$; i.e. at the ordinal level the two measurement scales coincide [31].

This conclusion explains the experimental confirmation of the theory, although our equations refer to physical and not to psychological measures.

As the α coefficient of transparency and the t measure of the reflectance of the transparent layer are physical measures, all the ordinal predictions (> , <) deduced from the equations measuring the above mentioned coefficients are valid for the perceptual counterpart.

This is the case with regard to the necessary condition for transparency $/p-q/ < /a-b/$. Reflectances a, p, q, b are measures of stimulation. As the order in the physical scale allows us to predict the order in the psychological scale, we do not need to measure a p q b with a photometer in order to determine whether the necessary condition is respected; it is enough to see whether the difference in lightness between p and q is less than the difference in lightness between a and b.

But coefficient α also is a physical and not a psychological measure. However just because the scale of the stimuli respects the order of the scale of the impressions - we can verify the prediction that if $\alpha_1 > \alpha_2$ transparency in situation 1 is greater than transparency in situation 2.

Finally let us consider the necessary conditions of transparency "$/p-q/ < /a-b/$" and "if $(p > q)$, then $(a > b)$" (see 2.1 and 2.2 above). If the first condition is not respected we have $\alpha > 1$; and if the second condition is not respected, α becomes negative ($\alpha < 0$). The profs given in 2.1 and 2.2 referred to the fact in equations (1) and (2) α and $(1-\alpha)$ are the coefficients of a or b and t. In the first case if $\alpha > 1$, then $(1-\alpha) < 0$ and therefore since $(1-\alpha)t$ becomes negative, the T region would receive a negative quantity of color, which is meaningless; in the second case, where $\alpha < 0$, the A

[31] Monotonic dependence.

and B regions would receive a negative quantity of color.

In these cases also, the conclusions being founded on asymmetric relations (>,<) and not on measures, are confirmed by perceptual results.

But t being a reflectance, meaninglessness of α a, α b or $(1-\alpha)$t negative becomes clearer, since it would mean that surfaces A, B or T absorb more light than they receive.

Besides, taking into account the model of the episcotister, we see that it is not necessary to consider α as a coefficient of t in order to conceive the absurdity of $\alpha > 1$ and $\alpha < 0$. In the first case (namely $\alpha > 1$) the episcotister should be less than 0° (if the episcotister's size is 0°, the empty sector, $\alpha = 1$); in the second case ($\alpha < 0$), the episcotister should be more than 360°. And when stimulation is impossible, there is no possibility of a corresponding sensory impression.

In other words, when ordinal predictions are made, and supraliminal differences are considered, the predictions are valid even if they are based on physical instead on psychological measurements. This is the reason why the inferences quoted in section 2, which are based on data used at the ordinal level were all confirmed.

Direct comparison between calculated and estimated measures is a different problem. Here it is clear that as the physical and psychological scales are different, the stimulus measures cannot result equal to the psychological estimations.

However, when the function connecting the two scales of measurement is known, it is possible to calculate the psychological measure corresponding to a stimulus measure.

In the present state of knowledge the lightness of the transparent layer can be predicted. The calculated t being a measure of reflectance, we can use the function relating reflectance t and perceived lightness t^* or simply the tables relating reflectance and the Munsell subjective lightness scale to obtain an approximated transformation from one scale to the other.

The same cannot be done for transparency, as we do not at present have a function relating physical and perceived transparency. However recent research by Masin, Cavedon and Bressan on a special type of transparency (partial transparency) [32] yelds some preliminary knowledge as to the relation between estimated transparency and α. The results are not sufficient to approximate a function relating the two scales, and they stress a further difficulty. Estimated transparency is not only related to the α coefficient but also to the lightness of the transparent layer. This factor, observed as early as 1921 by Tudor Hart when working under Koffka's supervision [33] was found acting in two opposite directions: all other conditions being equal, transparency increases when the transparent layer is approximately black, and decreases when it is approximately white [34].

7. *Prediction of the degree of perceptual transparency*.

A further development of the theory has been suggested by Beck's results [35].

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[32] Partial transparency is an extreme form of non-balanced transparency, where α or $\alpha' = 0$ and therefore only one of the p and q regions is transparent and the other opaque. The advantage of experimenting with this type of transparency is that t is a known term and therefore, since only α is unknown, one equation suffices to calculate it. (See Appendix).

[33] See B. Tudor Hart (1928) and Koffka (1935) p. 263. This point has always been stressed in our previous papers (see Metelli, 1974, 1975).

[34] Using the episcotister, the size of the sectors being the same, the perceived transparency is much greater when the episcotister is black ($t = .05$) than when the episcotister is white ($t = .86$).

[35] See fn. 12 at page 16 and Appendix.

In this paper we pointed out that the algebraic theory of perceptual scission concerns stimulation, as it specifies the necessary stimulus conditions for perception of transparency; these are physical conditions giving rise to the actual phenomenon. Besides, when the relations between physical and perceptual scales are known, the stimulation data allow us to make a series of predictions regarding the perceptual properties of a given situation of transparency.

It is possible however to follow a different way and try to state equations in terms of perceptual data, in order to reach directly a quantitative prediction of the perceptual parameters of transparency.

Let us start from the stimulation at the level of the sense organ and consider the processes originating there and giving rise to color perception.

First of all is must be pointed out that the parallelism between the scission and fusion processes no longer holds at the stimulation level. Using an episcotister with an homogeneous ground a fusion color is perceived by the subjects, and this color can be measured with a photometer. But if a bicolor ground is used, the photometer measures one or other of the fusion colors, while subjects perceive transparency. This fact suggests that chromatic scission is a psychophysical process taking place at a higher level.

We may hypothesize that scission is a process taking place at the level of color perception; in other words that the perceived colors and not the corresponding stimulations are the data from which we must start in order to calculate the perceived properties of the resulting scision, that is of the transparent layer.

Let a^*, b^*, p^*, q^* be the perceived lightness values of the four regions in the model of Fig. 3, when transparency is not perceived [36]. The process we purpose to describe is

$$p^* \begin{array}{l} \nearrow a^* \\ \searrow t^* \end{array} \qquad\qquad q^* \begin{array}{l} \nearrow b^* \\ \searrow t^* \end{array}$$

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[36] Taking an analytical attitude, so e.g. trying to evaluate the color of one of the four regions in Fig. 3, transparency disappears.

The starting point concerns the impressions of lightness a^*, b^*, p^*, q^*, which we can consider as known terms, as they can be, (or have been) estimated by a group of subjects [37]; while we consider <u>unknowns</u> the proportions α^* and $(1-\alpha^*)$ in which the reduction [38] color splits into the two scission colors and in case [39], the lightness $\underline{t}^*$ of the transparent layer.

Then let us go back to reflectances $\underline{a}$, $\underline{p}$, $\underline{q}$, $\underline{b}$, and $\underline{t}$.

We know from equations (1) that $\underline{p}$ is the weighted average of $\underline{a}$ and $\underline{t}$, and from equation (2) that $\underline{q}$ is the weighted average of $\underline{b}$ and $\underline{t}$. Starting from this knowledge (Metelli, 1978, p. 126) or through a rigorous deduction (Metelli, 1974a, pp. 105-108) we reached the conclusion that either $a > p > t$ or $t > q > b$.

Since the perceptual scales of measurement respect the order of the corresponding physical scales, the above relations are also valid for the perceptual measures, i.e.

either $a^* > p^* > t^*$ or $t^* > p^* > a^*$

and respectively either $b^* > q^* > t^*$ or $t^* > q^* > b^*$

We can represent the above measures with a diagram where we consider the relation $a^* > p^* > t^*$. Measure $\underline{p}^*$ (i.e. the measure of the segment Op^*) is equal to $\underline{t}^*$ (i.e. the measure of the segment Ot^*) plus a fraction x_1 of the segment $a^* - t^*$ (as segment $t^* a^*$ is equal to segment Oa^* minus segment Ot^*).

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[37] Or whose reflectances are known and the corresponding lightness values are otaimed from from a perceptual lightness scale (F. ex. Munsell).

[38] That is the color that is perceived when perceptual scission does not occur.

[39] When <u>partial</u> transparency is studied, $\underline{t}^*$ is one of the known terms (See. Appendix).

The equation for the scission of the perceived (achromatic) color $\underline{q}^{*}$ can be deduced in the same way from the asymmetric relations $b^{*} > q^{*} > t^{*}$ and $t^{*} > q^{*} > b^{*}$ and is

$$q^{*} = \alpha'^{*} b^{*} + (1-\alpha'^{*})t'^{*} \qquad (6)$$

Again, if $\alpha^{*} = \alpha'^{*}$ and t^{*}, the system of two equations can be solved for α^{*} and t^{*}, that is

$$\alpha^{*} = \frac{p^{*} - q^{*}}{a^{*} - b^{*}} \quad (7) \quad \text{and} \quad t^{*} = \frac{a^{*}\, q^{*} - b^{*}\, p^{*}}{(a^{*} + q^{*}) - (b^{*} + p^{*})} \quad (8)$$

Then it is possible to obtain the unknown proportions α^{*} and $(1-\alpha^{*})$ of perceived color of the surfaces resulting from the scission process, and thus to predict the degree of perceived transparency, starting from the perceived linghtness of the four colors implied in the process.

It is clear that in this case α^{*} is different from α but it has however the properties of a coefficient of transparency: the same considerations that brought us to this conclusion for α are valid also for α^{*}. And it is a coefficient of perceived transparency [41].

There is, however, an interesting relation between the equations (5) and (6) of perceived transparency and Talbot's law [42]. Clearly as Talbot's law regards physical measures of colors (in our case the reflectances) it cannot be valid if reflectances are substituted with measures of perceived lightness. But using equation (5) we can predict the measure of the perceived fusion color starting from the perceived colors of the two components. Then the parallelism between fusion and scission appers again at the perceptual level as well [43]

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[41] Then α^{*} formula, that has been used by Beck, can be deduced from the theory of transparency as a chromatic scission.

[42] I owe the suggestion of this relation to Dr. S. Masin.

[43] ./. p. 32.

(3) Perhaps it is useful to give an example

	Reflectances	Munsell neutral scale
data	$a = 85{,}77$	$a^{*} = 9{,}315$
	$p = 76{,}33$	$p^{*} = 8{,}89$
	$q = 3{,}24$	$q^{*} = 2{,}04$
	$b = 0{,}63$	$b^{*} = 0{,}59$
	$\alpha = 0{,}86$	$\alpha^{*} = 0{,}78$
	$t = 19{,}07$	$t^{*} = 7{,}34$

In this case the coefficient α^{*} of perceived transparency is 0,78, while the coefficient α of transparency on the stimulus scale is 0,86. Much bigger differences are obtained in the case of partial transparency, as it will appear in the Appendix. However, apart from being the psychological coefficient of transparency α^{*} could be used for predicting the fusion color p^{*} (in terms of the psychological scale), starting from (psychological) measures of a^{*} and t^{*} and using formula (5), or the fusion color q^{*} starting from b^{*} and t^{*} using formula (6), that is

$p^{*} = (0{,}78)(9{,}315) + (1 - 0{,}78)(7{,}34) = 8{,}88$

and $q^{*} = 0{,}78(0{,}59) + (1 - 0{,}78)(7{,}34) = 2{,}07$

The calculated perceptual values p^{*} and q^{*} correspond to the data and therefore to the reflectances p and q predicted by Talbot's law. Using the coefficient α^{*} we can therefore predict the fusion color in perceptual units starting from the perceptual values of the components of the mixture.

CONCLUSION

First of all the critical examination of the theory developed in this paper, based on the model of the episcotister, allowed us to clarify the meaning and the scope of previous results.

Having established that the parameters of transparency, α and $\underline{t}$, are physical measures, given the correspondence of physical and perceptual scales at the ordinal level (monotonic dependence) it followed that qualitative deduction and deduction about asymmetric relations (>,<) drawn starting from physical scales were justified.

But the ascertainement that α and t parameters are physical measures gave rise to the requirement to obtain the correspondent perceptual measures.

The approach to the perceptual measures α^{x} and t^{x} has been direct, deducing the transparency equations in terms of perceptual measures. The terms of these equations can be obtained either by having recours to direct lightness estimation of the achromatic colors of the display (estimation which is much more reliable) or, more simply by reading on the Munsell Neutral Scale the perceptual values corresponding to the known reflectances. The new equations of transparency require wide experimental testing and appear promising as they offer the opportunity to restate various problems in a new perspective.

It has however to be stressed that the knowledge of the transparency equations referring to perceptual scales does not change radically our knowledge about the perception of transparency.

APPENDIX

Phenomenal transparency appears in different forms, but only the more common form, complete transparency, has been considered in this paper.

It is however appropriate to take into consideration a special form of Transparency, because Beck's results results refer to it. This form of transparency has been called partial transparency, because only one of the two regions, P or Q is perceived as transparent, while the other one is perceived as opaque (Fig.21). In fact, in the most typical cases of partial transparency we perceive one surface as transparent only where it is perceived as overlapping another surface (Fig.22) [44].

In the case of partial transparency the mathematical treatment becomes very simple.

We start still from the two equations

$$p = \alpha a + (1-\alpha)t \qquad (1)$$
$$q = \alpha' b + (1-\alpha')t' \qquad (2)$$

Let us consider the case where, of the paradigmatic figure (Fig. 21) the P half circle is transparent, while the Q half circle is opaque.

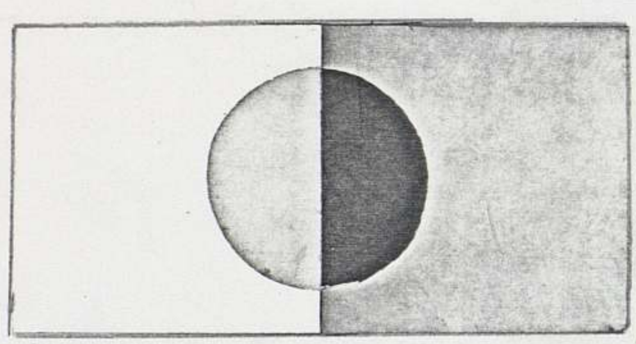

FIG. 21.

[44] Figures where partial transparency is perceived are in general reversible. Therefore what is Q in one "version" becomes A in the other version, or, in other words, a and q exchange their functions.

If the Q region is opaque, there is no color scission in this region, the inferior layer receives no color ($\alpha' = 0$) and all the color of Q goes to the superior layer T, which identifies with Q.

Then

$$q = (0)b + (1 - 0)t'$$
$$q = t'$$

therefore we can substitute q for t'; and if $t' = t$, [45] equation (1) becomes

$$p = \alpha a + (1-\alpha)q$$

In this case there is only one unknown,

$$\alpha_{part} = \frac{p-q}{a-q}$$ [46]

[45] In general the hypothesis is acceptable, because the difference between P and Q, when transparency of P is perceived, appears to be due, not do difference in color, but in density. (See Metelli and al., 1981, Section 3).

[46] It is opportune to distinguish α_{part} (coefficient of partial transparency) (from α coefficient of complete transparency) as the two coefficients are quite different when the two types of transparency can be perceived in the same display (See Metelli and al., 1981, Section 5).

It has to added that for Partial transparency also, the equation of the coefficient of transparency (α_{part}) in terms of perceived colors used by Beck with the items of the Munsell Neutral Scale, can be easily deduced from the theory of transparency as perceptual scission, starting from equations (5) and (6) and following the same reasoning used above for deducing α_{part} from equations (1) and (2) or having recourse to a diagram similar to that used to deduce equations (5) and (6), and starting from the necessary condition for Partial transparency $a > p > q$ or $q > p > a$.

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Il redattore: Marco Sambin
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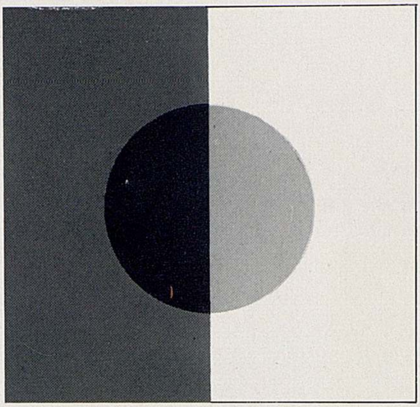

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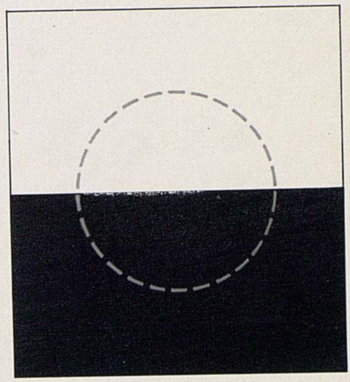

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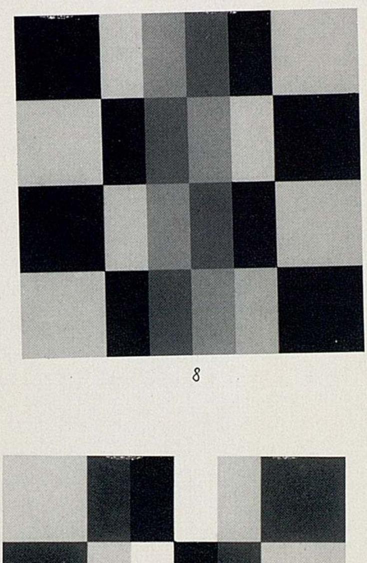

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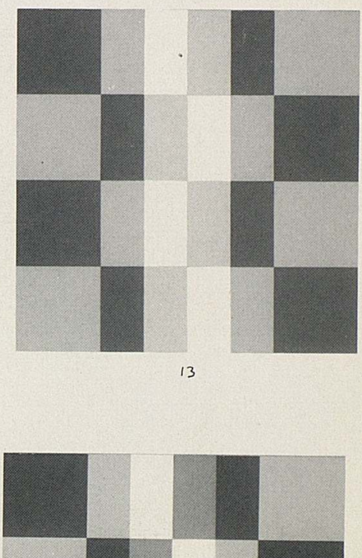

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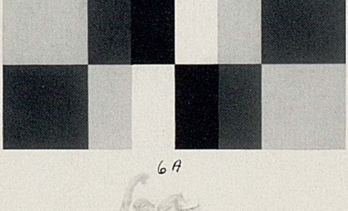

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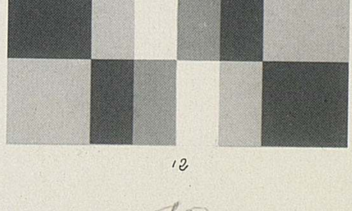

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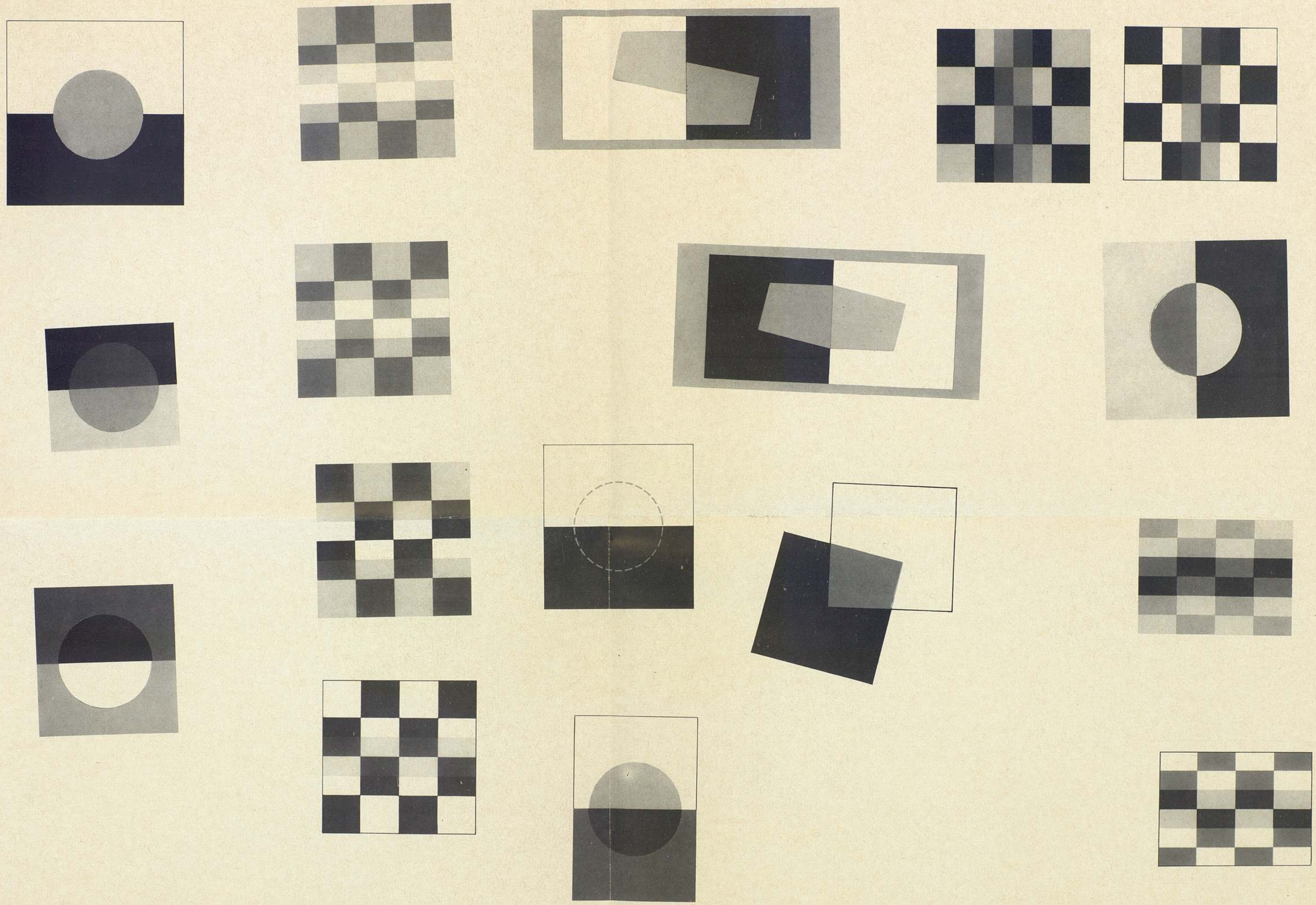

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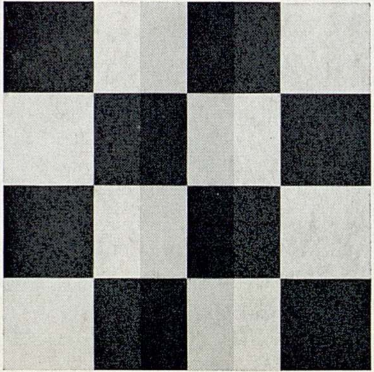

Fig 10

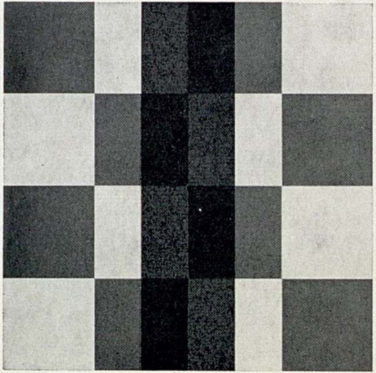

Fig. 11

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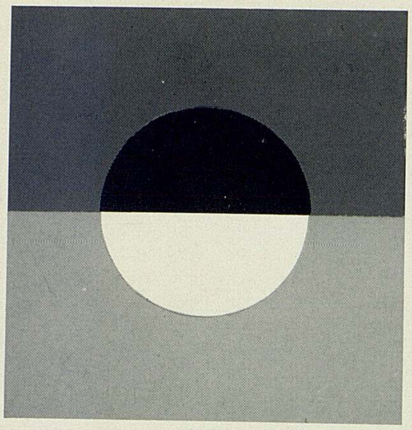

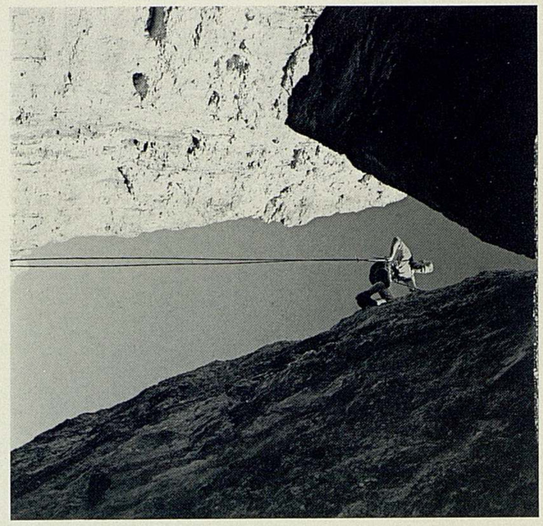

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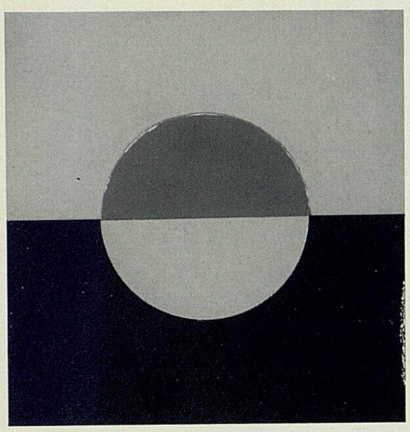

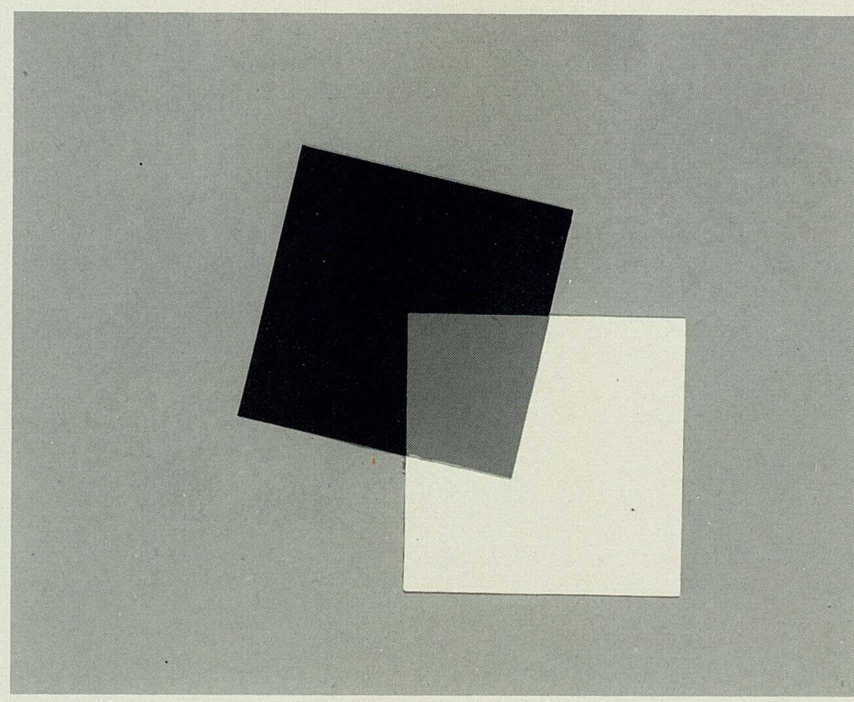

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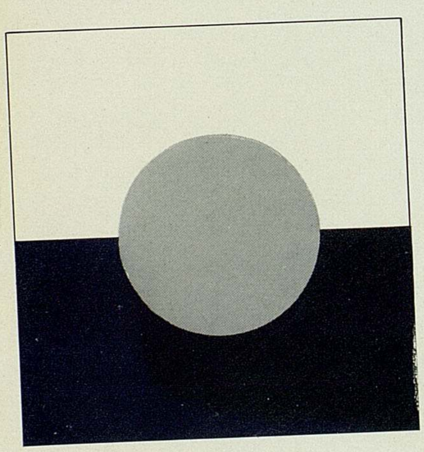

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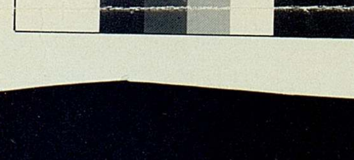
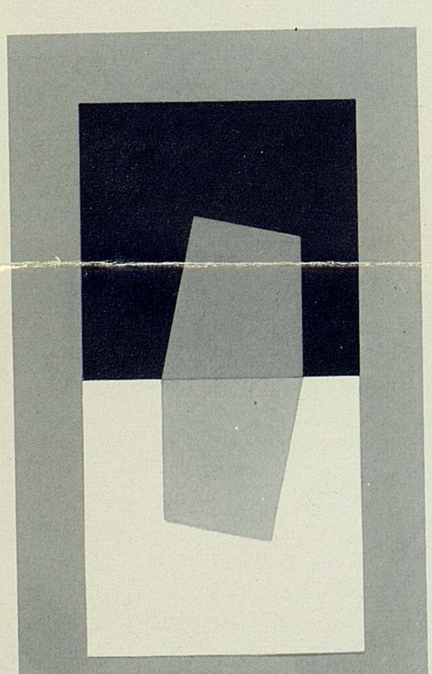
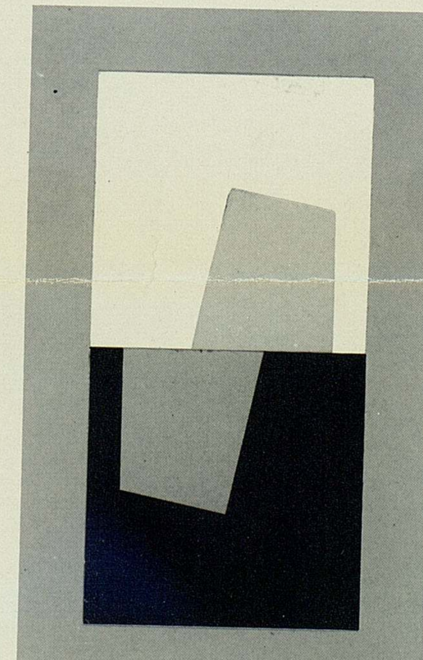






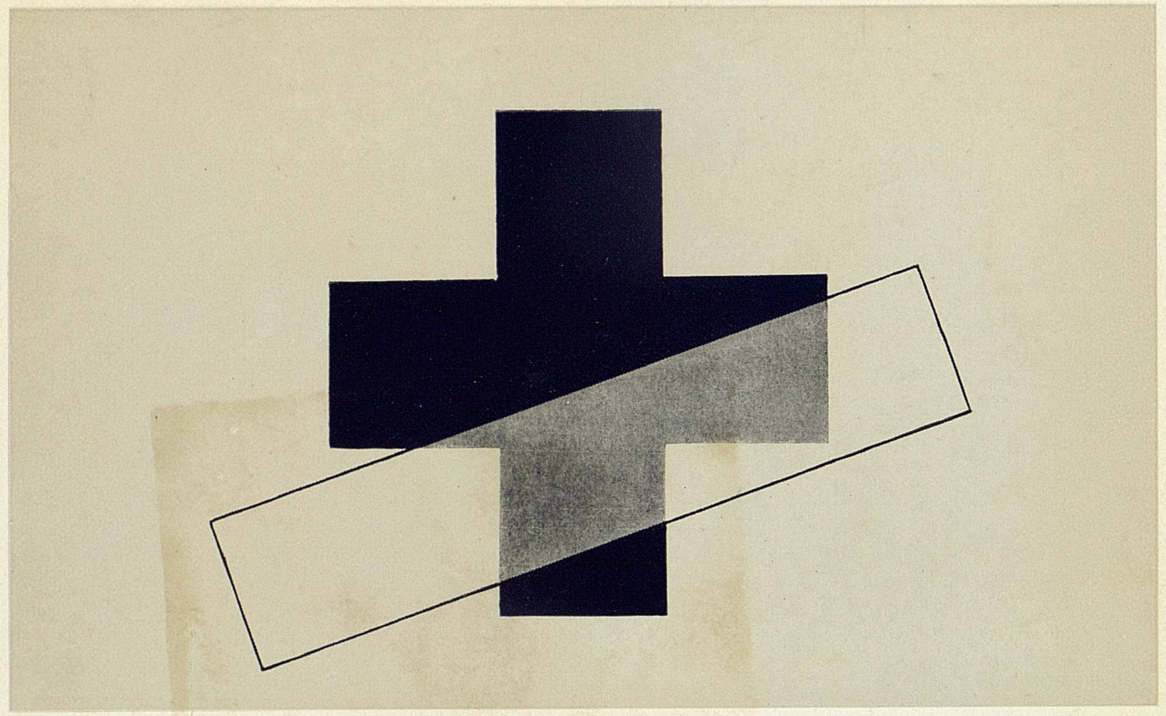
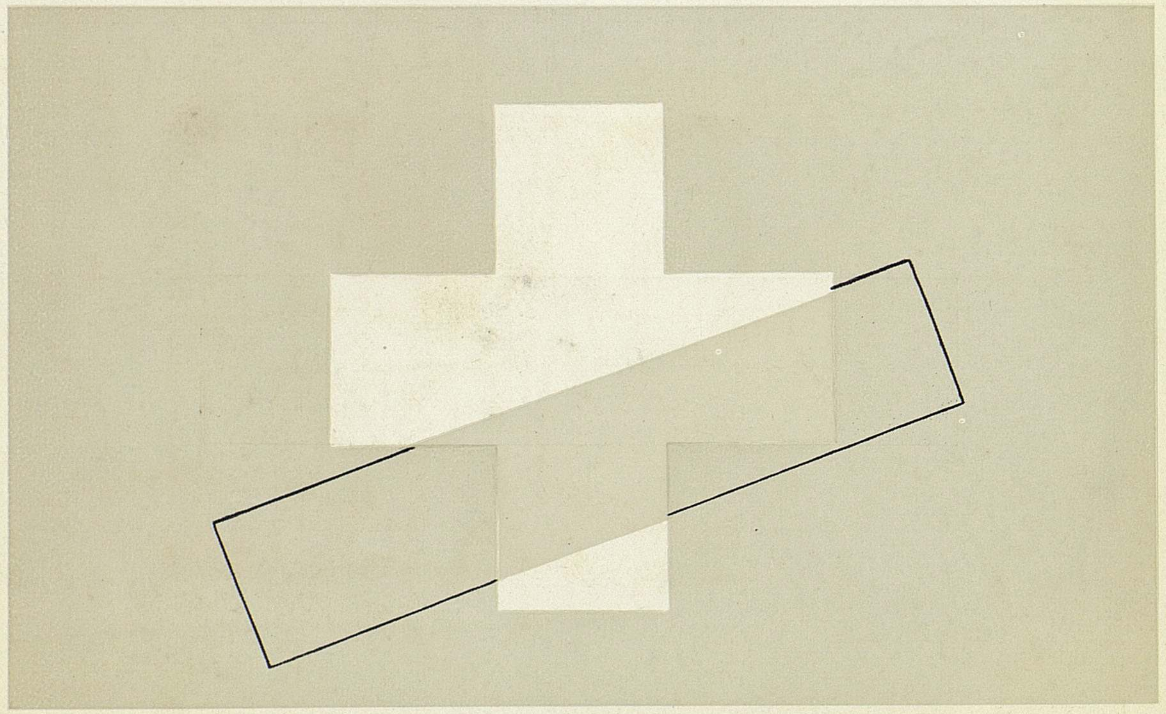


Fig. 9 e 10 Anche per la zona di sovrapposizione tra la figura superiore e lo sfondo avviene la scissione cromatica.



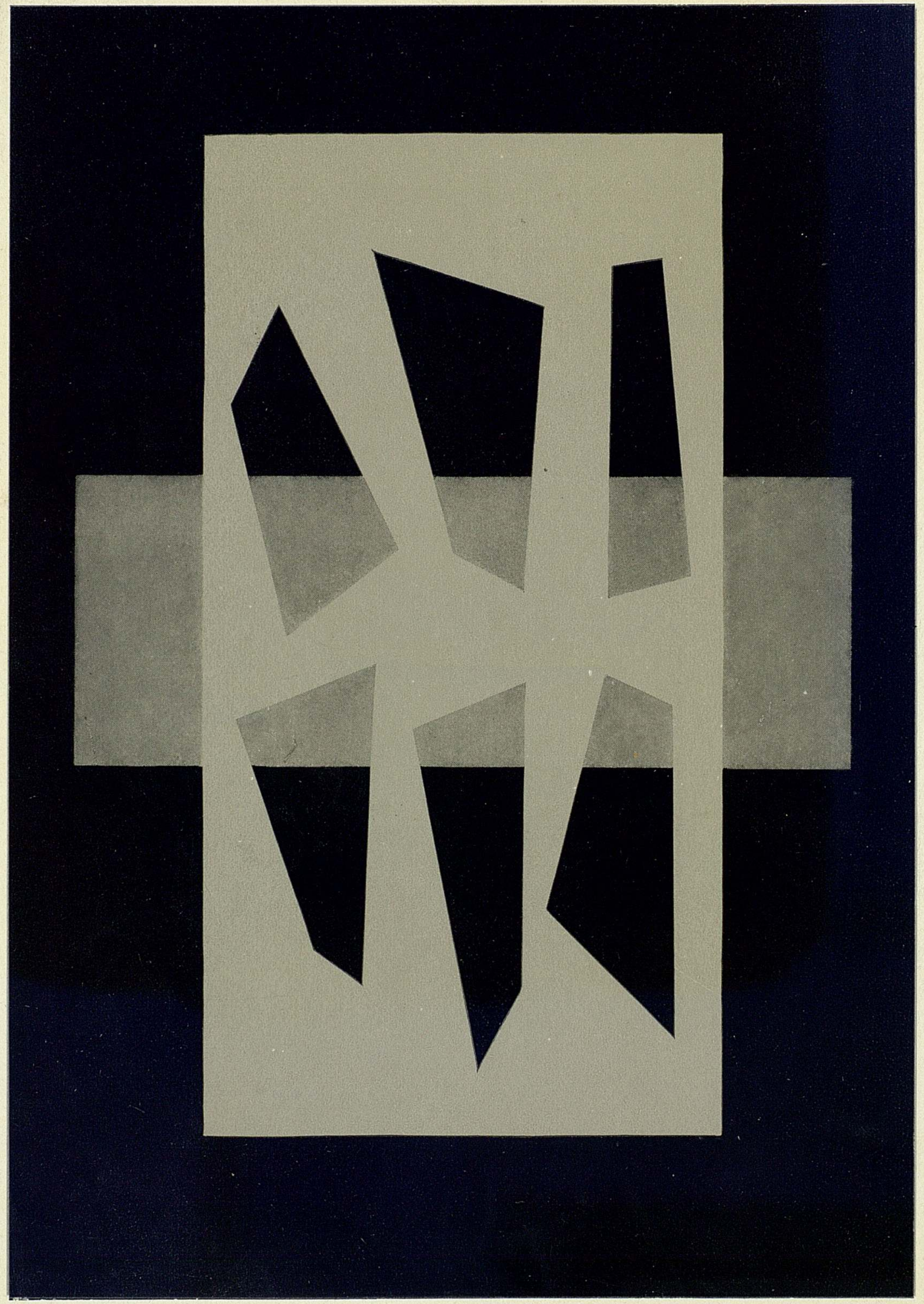


Fig. 11 La pellicola trasparente copre anche una parte dello sfondo.

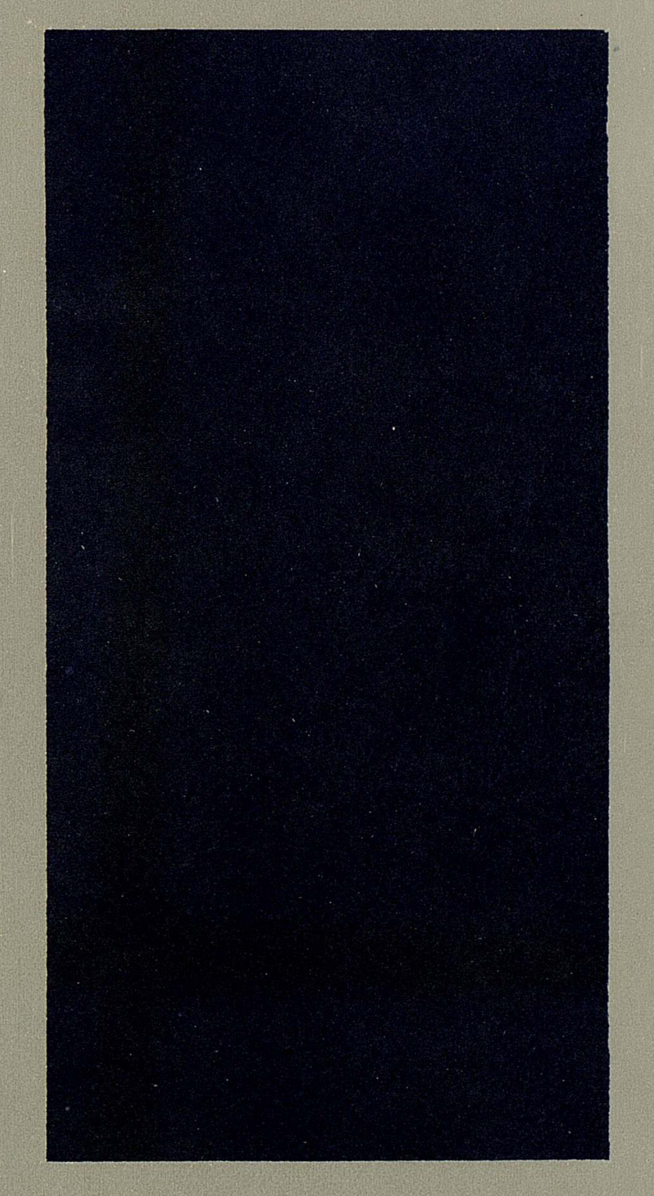
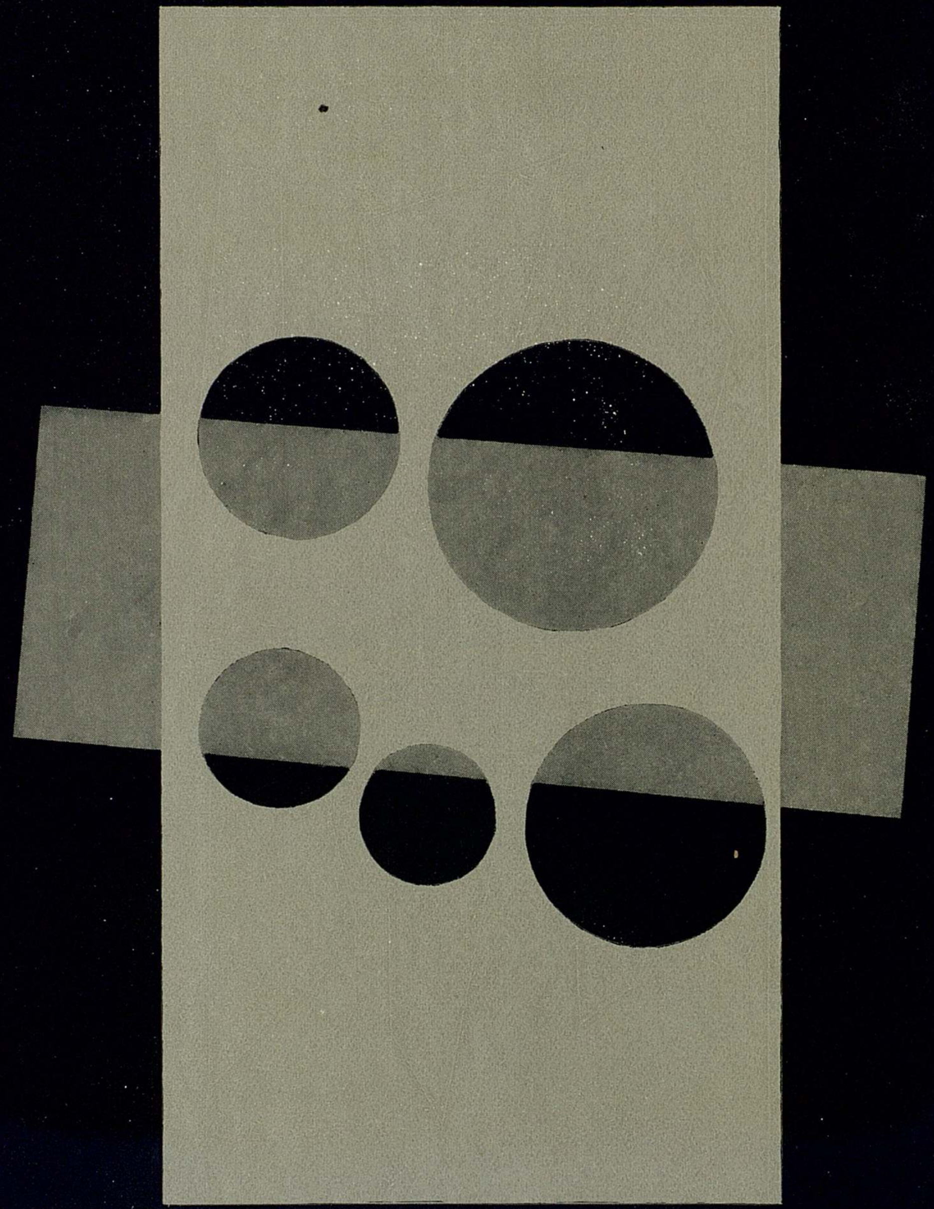


Fig. 12 *Ad una differente organizzazione tridimensionale di uno stesso complesso di stimoli corrisponde un diverso rendimento cromatico.*
Se si allontana lo schermo si facilita una organizzazione tridimensionale *senza* trasparenza: su uno sfondo nero, un rettangolo grigio scuro e, davanti a quest'ultimo, una «maschera» chiara con buchi attraverso i quali si scorgono parti dello sfondo nero e parti del rettangolo grigio scuro.
In tal caso sparisce il «velo» trasparente e con esso la *diversità di chiarezza* tra zone ad eguale stimolazione.



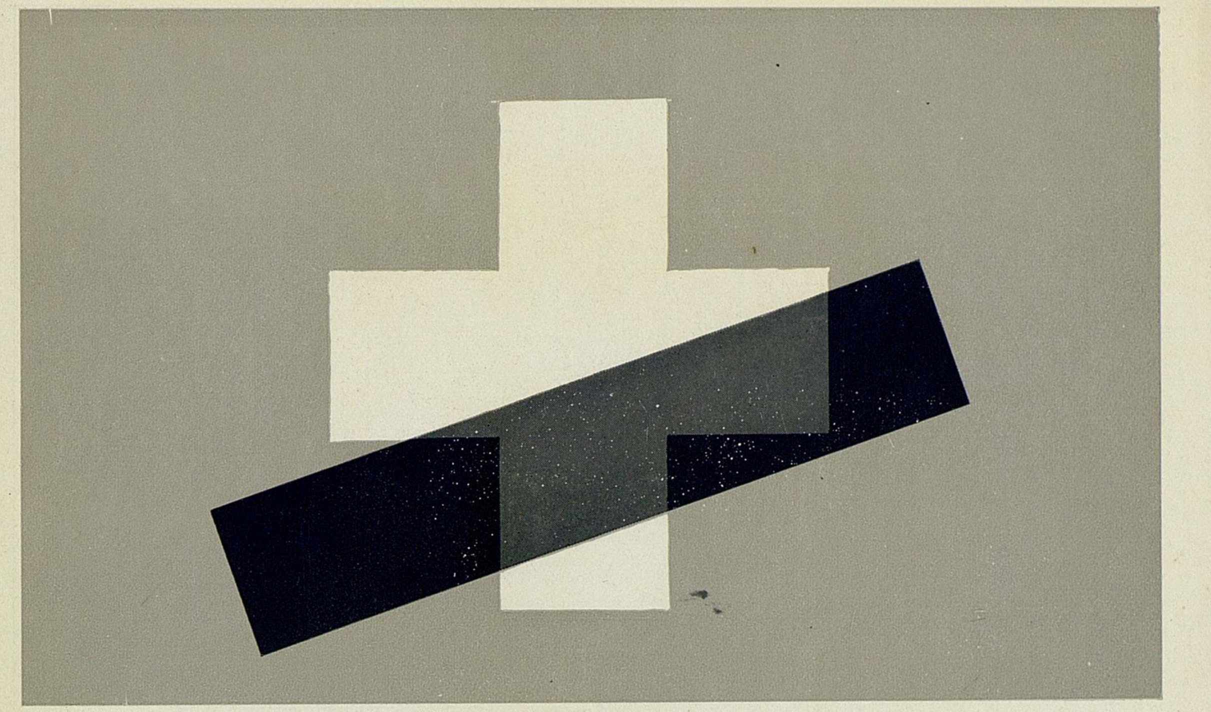
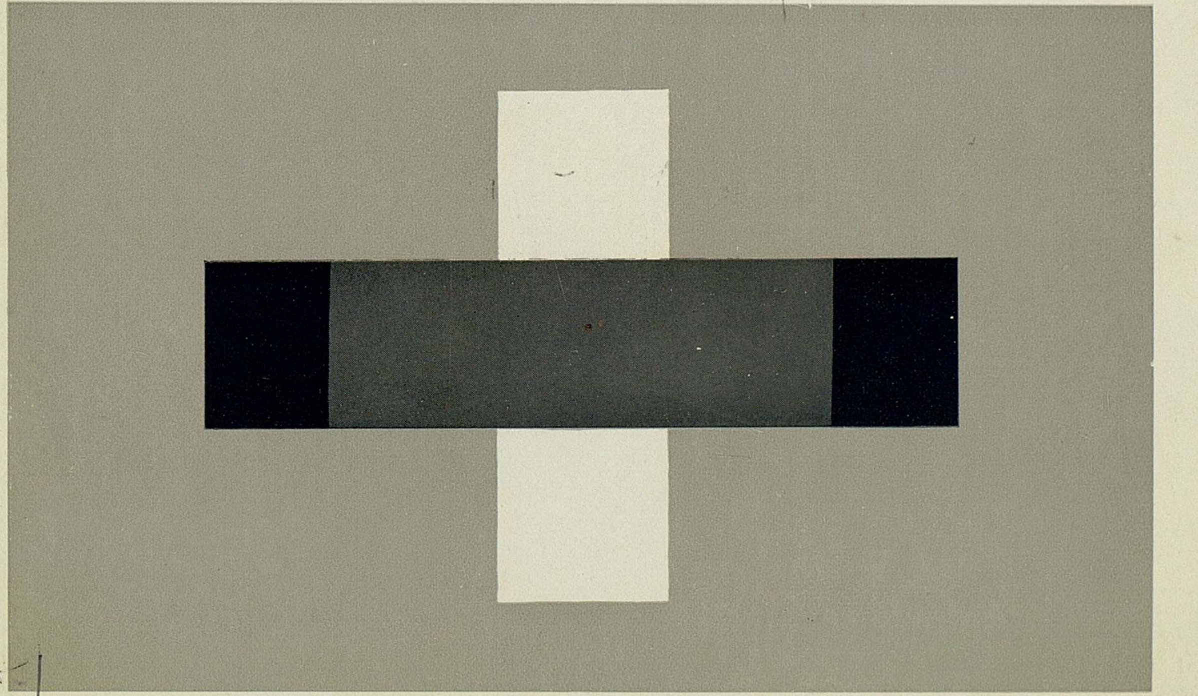
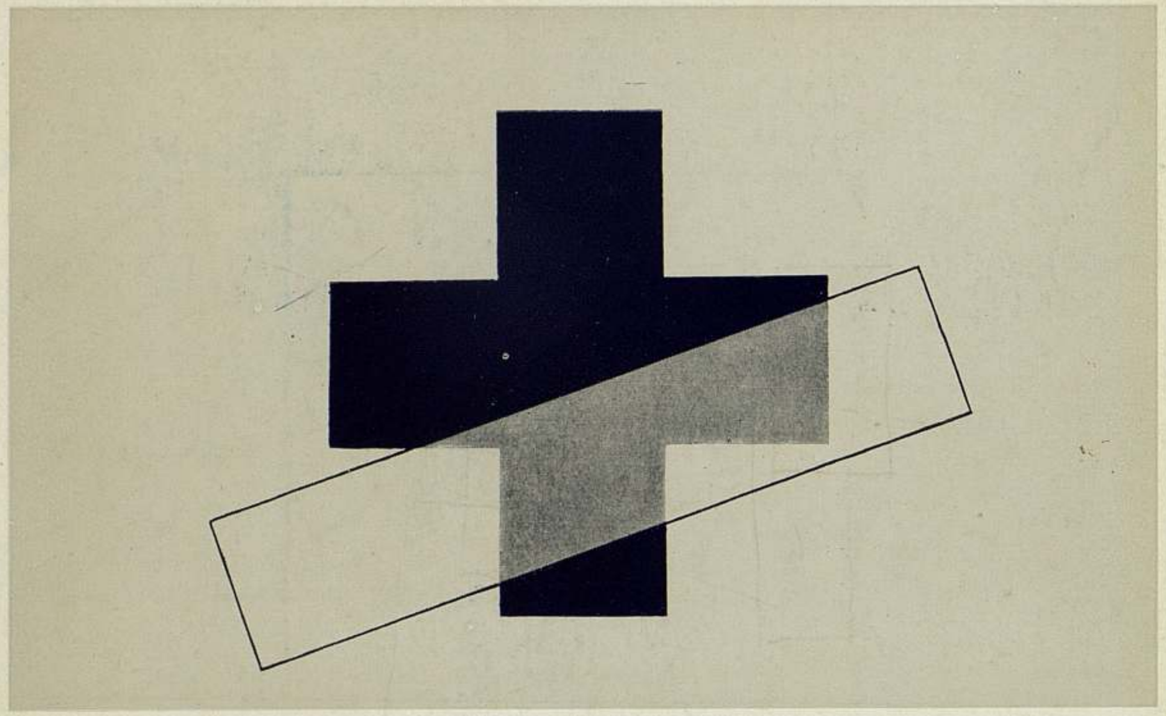


FIG. 2 *Una superficie opaca percepita come trasparente.*
La zona grigia sia costituita da un cartoncino perfettamente opaco incastrato tra due pezzi di cartoncino nero. (da W. METZGER).

FIG. 7 Nonostante la protrusione di una figura rispetto all'altra e la eterogeneità cromatica, la zona « comune » non appare trasparente (da W. METZGER).





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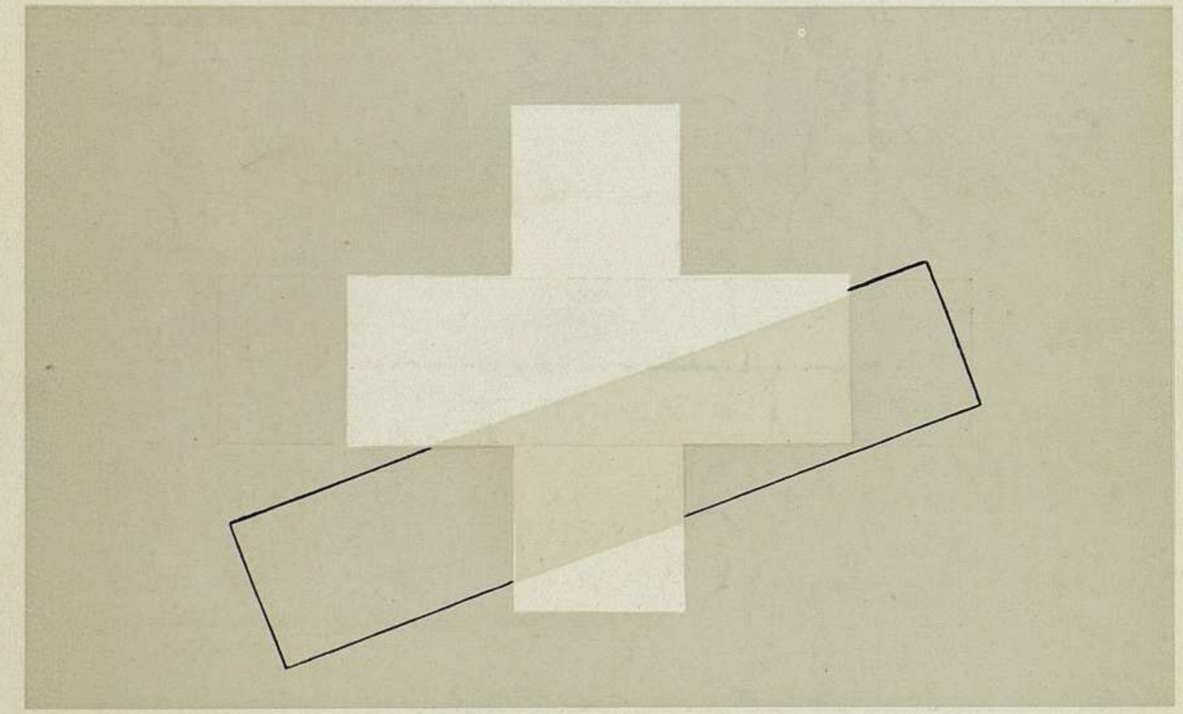

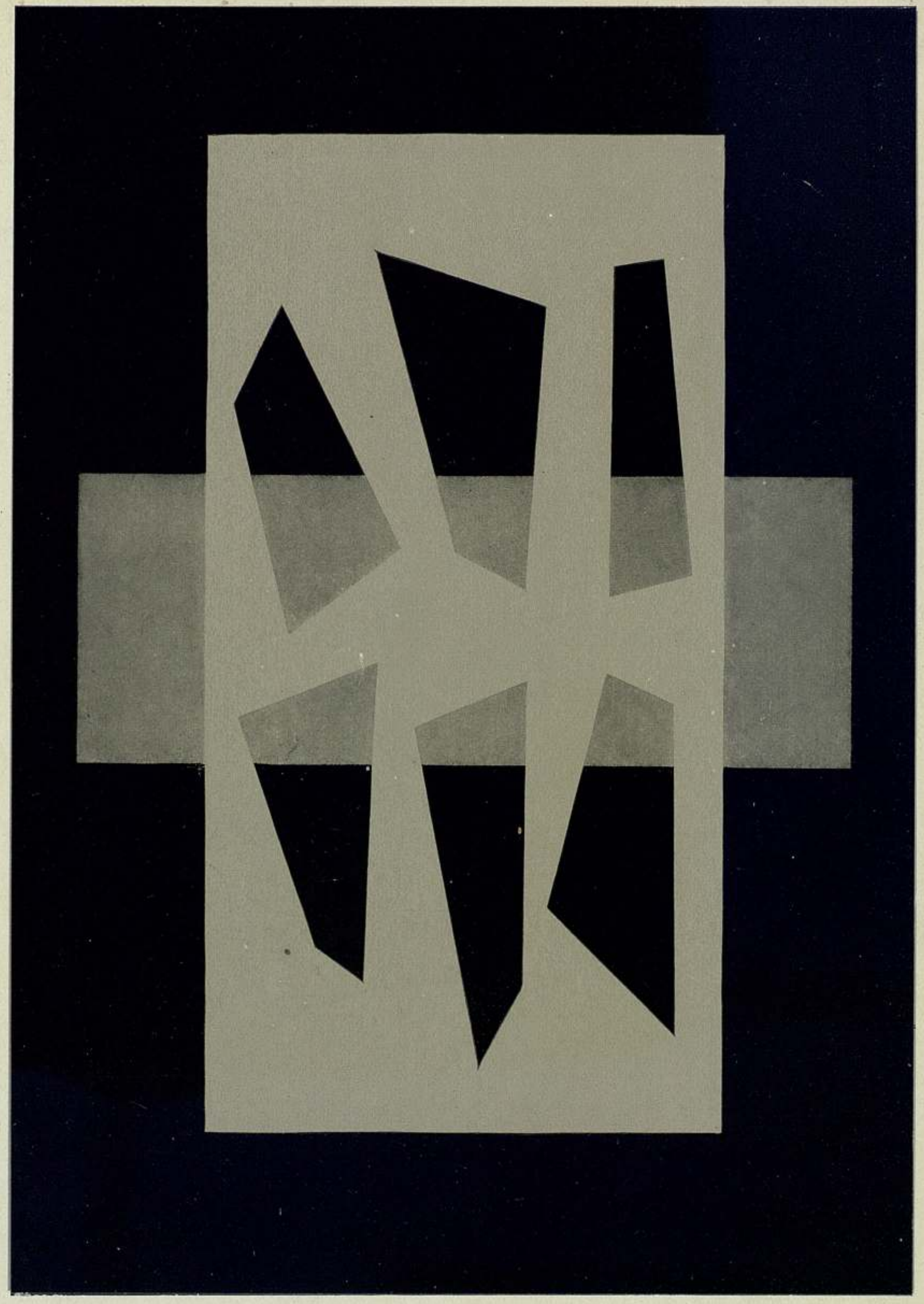

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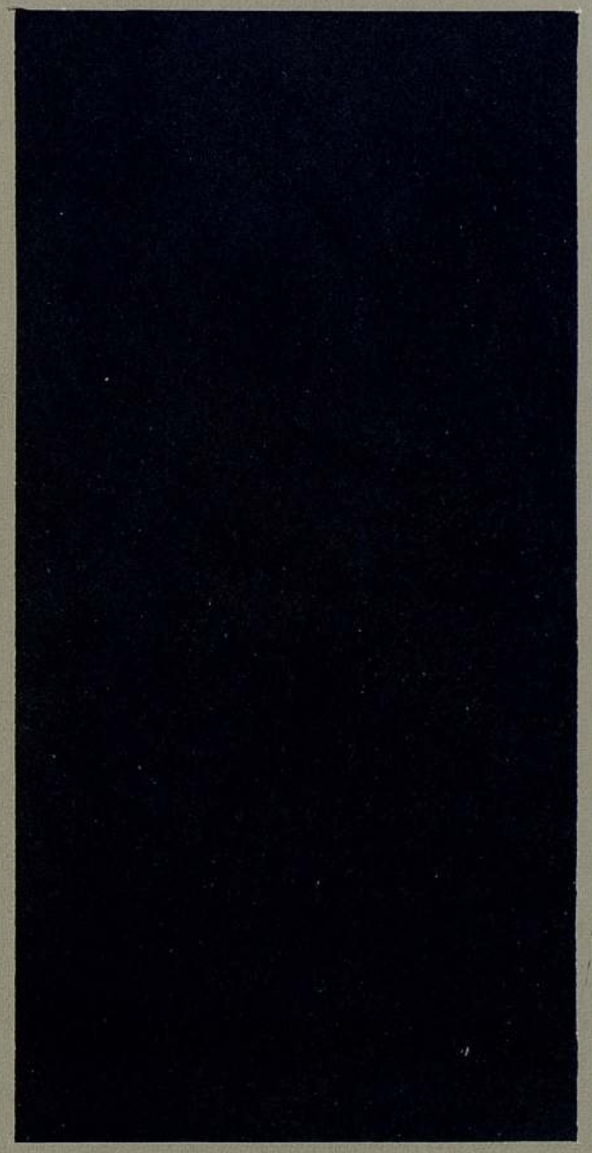

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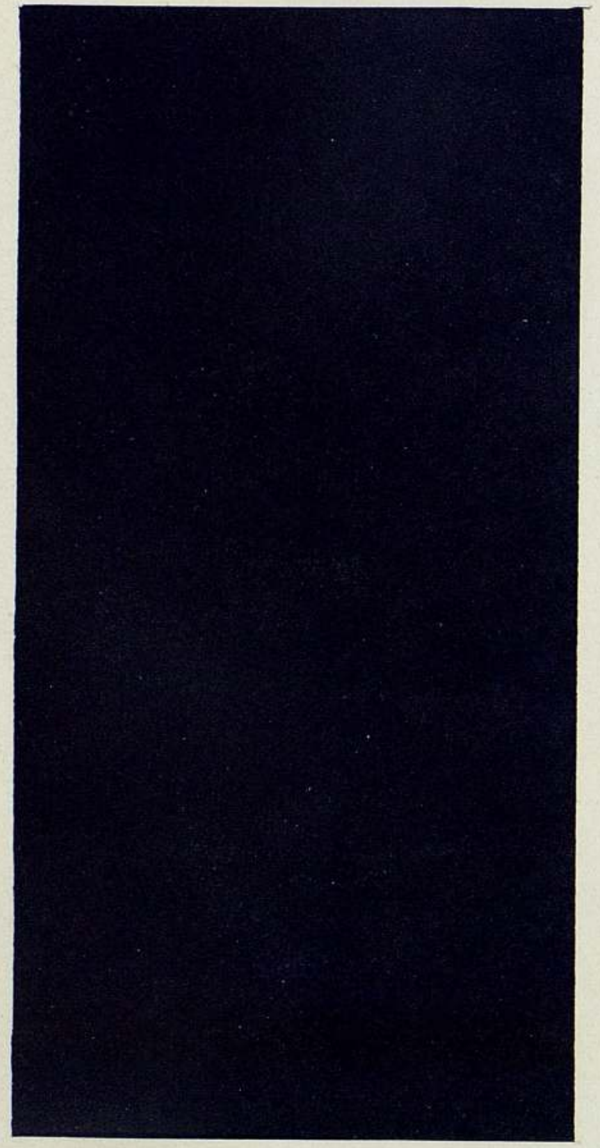

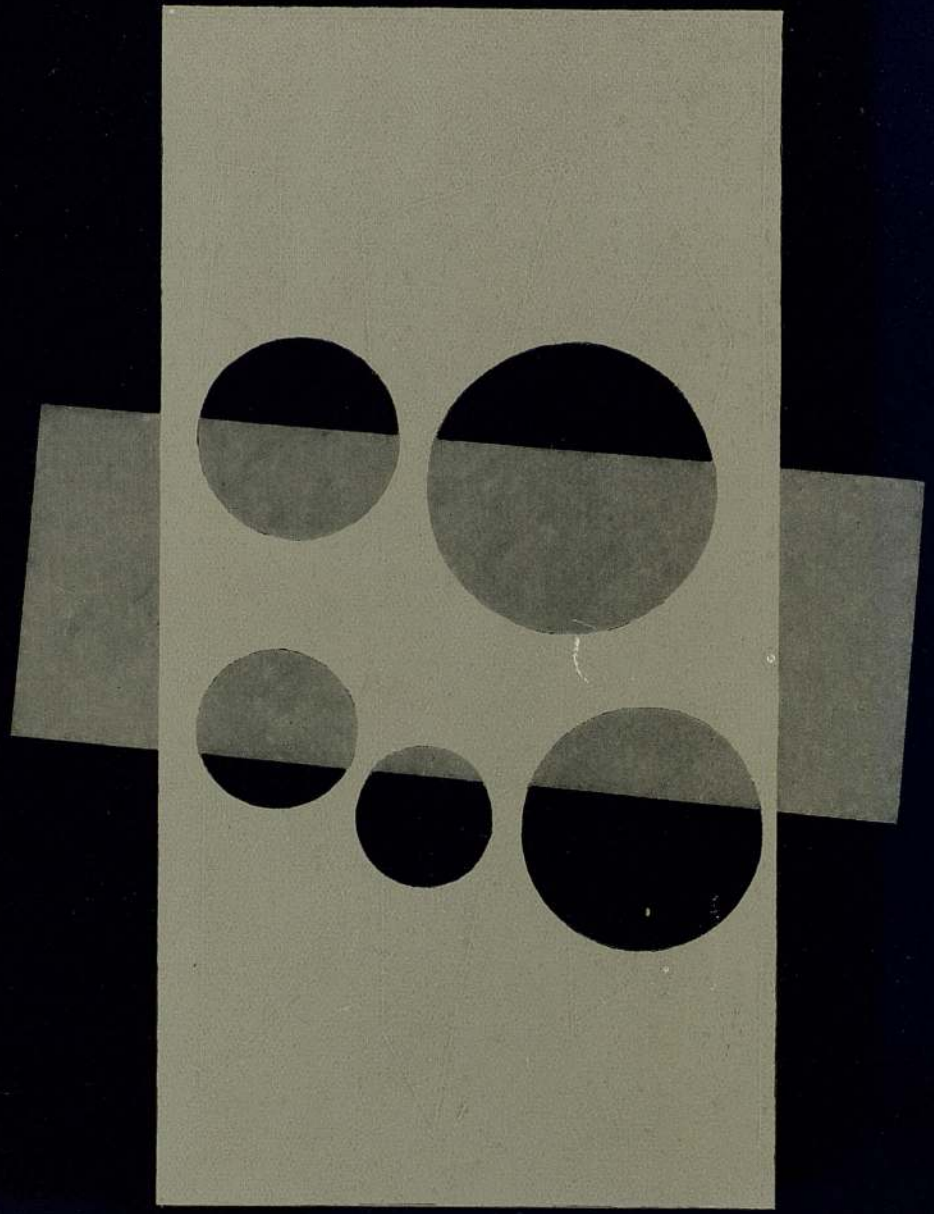

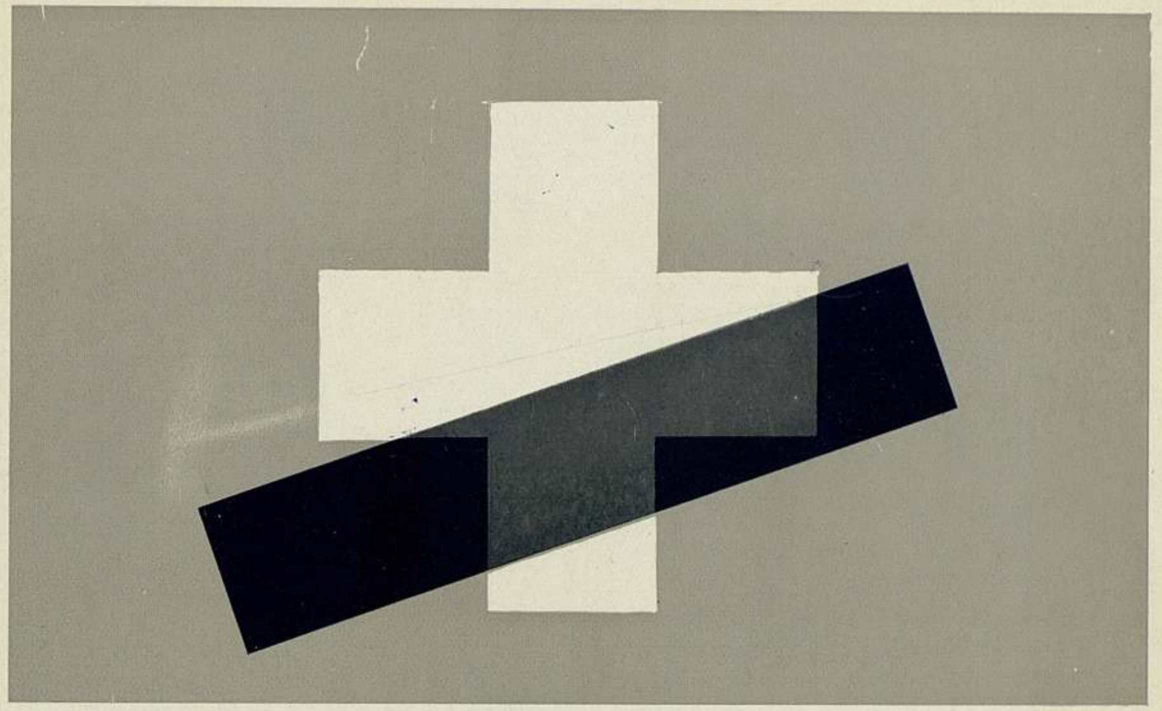

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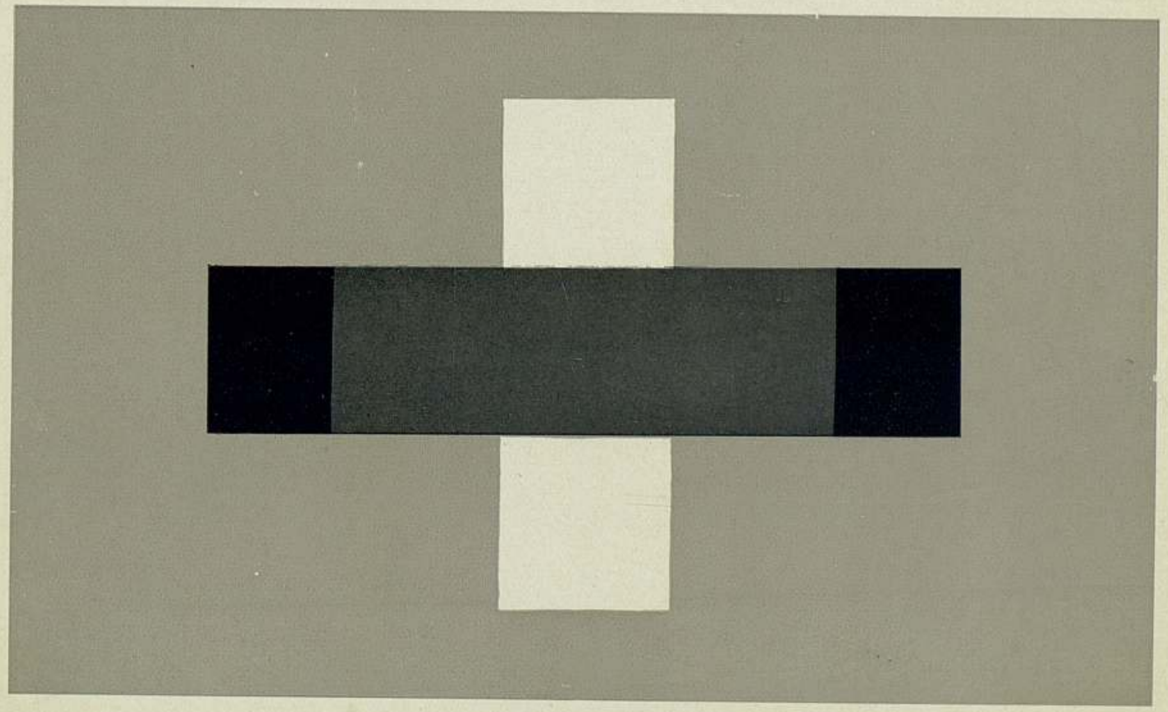

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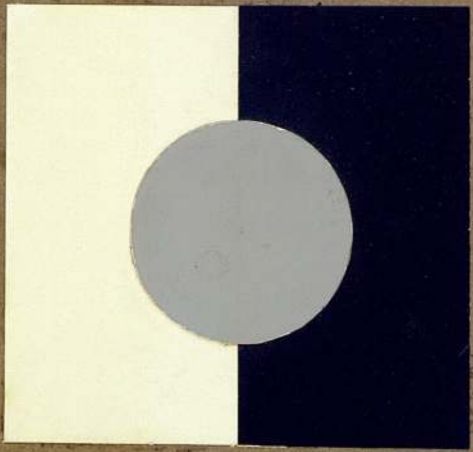

Fig. 4