Optical Art

Gerald Oster

The historical origins of optical art are traced. The features of the main techniques used by optical artists are discussed from a theoretical point of view. Such techniques include the juxtaposition of colors, three-dimensional projections, the use of optical components, and the application of the moiré technique. An optical theory of the appearance of edges based on the superposition of the after-image is presented. It is suggested that the highly geometrical figures of phosphenes can provide further inspiration for artists.

I. Introduction

Optical art is a new term. It has the connotation of art which is contrived to produce a strong visual effect. Optical art is usually characterized by pristine geometrical figures and its production is immaculate. Optical art is free of all representational forms, that is, shapes which we readily associate with ordinary objects around us are absent. Optical art goes beyond most of the abstract art of the past in that it uses simple forms deliberately for the purpose of evoking a pronounced visual stimulation. The total effect of an optical art piece may be agitating (to one art critic[1] it represents an "assault on the retina") or it can be calming, depending on the piece and the mood of the viewer. It is hardly ever dull, but certain examples can, for some people,[2] actually be unpleasant. The euphoric effects of one piece, at least, may be illustrated by an anecdote. One of my pieces, a moiré construction, where a parade of spots (diamonds) seemed to move with the viewer and to extend out in space, was on display in the lobby of a laboratory at the Rockefeller Institute. Some of the research workers told me that my piece gave them a feeling of optimism as they entered the laboratory ("this is going to be my lucky day").

Optical art is an unfortunate term since *all* visual art is optical. Whether or not one is able to explain visual impressions in terms of the science of optics, it is usually agreed that all visual phenomena up to the point where they register on the retina fall properly in the domain of optics. Hence at this level, art is a branch of applied optics. The integration of the visual information by, at its lowest level, the nervous system immediately associated with the retina and by the brain (more specifically the visual cortex) properly falls in the domains of nerve physiology and of the psychology of perception. The view which the eye usually sees is so complex that most physicists would be reluctant to engage in an analytical study of the optics of the problem. Even in the relatively simple case of diffraction, the conditions of Fraunhofer are much preferred over the Fresnel conditions for purposes of mathematical simplicity. It is from the complex picture that we abstract the relatively simple pieces of information for our survival and for our understanding of the world. Science now has the machinery, namely, the digital computer, for the solution of complicated optical problems. Furthermore, analog aids, such as the moiré technique, can help the optical scientist arrive almost intuitively at the answer to some involved problems in optics[3] such as those encountered in the visual scene.

An understanding of the real world is as important to the artist as it is to the scientist. For artists, however, their world includes the totality of perception and the emotional response one derives from it. Nowhere does art and science seem to be on such common ground for discussion as it does in optical art. Whether or not optical art conforms to one's tastes, it is worthy of consideration (or, better still, study) by scientists directly concerned with optics. Optical art is so intimately connected with visual information at its foundation that it is bound to be with us for a long time. Certainly optical art has much to teach the artists, and elements of it, at least, will be incorporated into much of the art of the future. Optical art is one manifestation of the cultural activities of our contemporary society; in particular, optical art makes us aware that man is an organism. Still further, it is executed with a precision characteristic of the technology of today. Regardless of its role in our culture, optical art can bring to the understanding and sympathetic viewer much the same joy and wonderment of the world that, say, an optical scientist felt as a student when he first appreciated the

The author is with the Polytechnic Institute of Brooklyn, Brooklyn, New York.

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magnificence of Maxwell's equations and their applicability to the whole of electromagnetic phenomena.

The purpose of this article is to acquaint the optical scientist with the essential technical aspects and the spirit of optical art. I am also using this occasion to expand the problem to a consideration of the role of optics in art. My particular qualification to write such an article (at the request of the editors of *Applied Optics*) is that I am both a scientist and an artist, albeit with a short experience as the latter.

II. Historical (in Reverse Chronological Order)

Optical art might be said to have received its official sanction by the art world with the exhibit this spring at the Museum of Modern Art in New York City, which bears the suggestive title *The Responsive Eye* and is being shown in various museums throughout the U.S.A.[4] An excellent descriptive catalog has been prepared[5] which contains pictures (many in color) of several pieces of the exhibit. In the present article we shall refer to many of the pieces illustrated in that catalog. As with all art, the full impact of the exhibit can only be fully appreciated by actually viewing the objects rather than reading about them. The black and white illustrations given in the present article are chosen for photogenic reasons and/or because they are reasonably susceptible to analysis. The pieces illustrated in the present article were not illustrated in the catalog for *The Responsive Eye*, but are typical of contemporary optical art.

Optical art was enthusiastically received by the public, judging from the large number of people who saw the exhibit at the Museum of Modern Art (nearly a quarter of a million in two months—a record for the museum). Many art critics were excited. One critic[1] saw in optical art the possibility of unifying art and science ("the great love match of the future"), whereas another critic[2] found the encroachment of a scientist into optical art as sufficient reason to discard it.

Artists, unlike scientists, usually do not have recourse to refute their critics (see the witty essay on this subject by Delacroix written in 1829[6]). French impressionism, which today is an acceptable form of art for most people, was in its time considered by a famous Parisian art critic as the work of "anarchists and madmen". Some artists not working in the optical art media may find this art devoid of emotion and hence refer to it as "non-art". The immediate sensory appeal of optical art and its exhiliatory effect does not, however, make it less art.

Optical art represents, to some critics at least, a respite from the undisciplined spirit and techniques of abstract expressionism which held sway for the past decade in American art circles. Abstract expressionism with its emphasis on the highly personalized and immediate (sometimes violent) emotional evocations of the artist often misses a rapport with the viewer. The feeling of the intensity of the technique of the abstract expressionist artists (witness the splash and dribble of the action painters), it seems to me, falls short of the visual impact of great masses of rich color which are also present on these usually huge canvasses. Furthermore, the texture of the generously applied paint can produce an interesting optical effect. Expression is also brought out forcibly and with a greater economy of means in many examples of Chinese calligraphy (see, for example, ref. 7).

Like any new movement in art (or in science, for that matter) optical art did not spring *de novo*, but had a long historical ground swell. Ten years ago a courageous Parisian art dealer, Denise René, was showing optical art in her gallery. Two of the finest contemporary optical artists, V. Vasarely and J. Albers, were exhibiting their pieces decades ago. Albers, who is now at Yale University, is an outstanding colorist and has had an enormous influence on optical art in America. He was a professor at the Bauhaus which before the Nazi times was the prime mover in the appreciation of the artistic aspects of modern technology. The influence of this school (which was contemporaneous with the important developments in quantum mechanics in Weimar Germany) is particularly apparent in the field of architecture. Many modern buildings in the United States bear the imprint of the Bauhaus. Vasarely, too, was trained in the Bauhaus tradition (the Hungarian equivalent). Most of the optical artists are, however, young people with an appreciation of the new technology. A group of optical artists in Paris, known as the Groupe de Recherche d'Art Visuel, regard themselves more as experimenters in visual phenomena rather than as artists in the conventional sense. Other groups have been formed in Barcelona and in various cities in Italy and Germany, and, reminiscent of the famous group of Parisian mathematicians, the Bourbaki, the artists in these groups often remain anonymous. The works of these artists are characterized by a joyfulness in spirit, and they utilize modern industrial materials to achieve interesting optical effects. As long ago as 1913 a few artists, notably Delauney, Malevich, Mondriaan, and Kandinsky, introduced the revolutionary concept of presenting abstract forms as an art in itself. These abstract artists encountered considerable resistance from the art world and, what is worse, neglect from the public (see, for example, ref. 8). Perhaps the most dramatic (and *optical*) of these painters was Malevich who had the temerity to show a white square on a black background as the complete piece. Even more daring was his later work "White on White". Very much in the modern spirit was Mondriaan, some of whose works consist of stark rectangles arranged in a mathematically precise fashion. Essentially his work is programmed art. The overtly self-conscious abstract art movement was accompanied with a personalized literature written by the more articulate abstract artists, much of which makes good reading (see, for example, refs. 9–11).

In the history of art Cézanne occupies the analogous position that Gauss does in the history of mathematics. Cézanne is the forerunner of much of modern art: although a representational artist, in that his landscapes resemble actual scenes, he is an abstract painter in that he abstracted from nature those optical elements which the eye particularly notices. I do not agree with some authorities (e.g., ref. 12) that he took liberties with nature. On the contrary, Cézanne paintings are a closer picture of what the eye sees than what we think of *a priori* as an edge, a plane, etc., with its strict adherence to formal notions of perspective and the like. Cézanne was an acute and patient observer of the visual world, and his edges, for example, represent greater reality of what the eye sees than what one imagines an edge should be. Later in this article a rationalization of Cézanne's technique of edges will be attempted. Cézanne's presentation of reality was more successful than the efforts of the Impressionists of his time, such as Monet. Monet's dazzling paintings, which were produced very rapidly, are a more personal and emotional impression of the instantaneous optical effect of an outdoor scene. The Impressionists used color in a unique manner to catch the surface highlights in a sun-drenched scene, but by and large they lost the feeling of solidity which Cézanne was able to capture.

Of all the nineteenth century French painters, Seurat stands out as being the most modern in spirit. Seurat applied his paint as dots of pure color (see below), "le pointillism", reminiscent of the halftone dot printing invented some years before by Talbot. The dots were arrayed in a carefully planned manner, which Seurat painstakingly worked out, to achieve remarkable effects of color and three-dimensionality all combined into a beautiful composition. His masterpiece "Sunday Afternoon on La Grande Jatte" is a veritable gold mine of optical devices. An analysis of his work has been made (e.g., ref. 13), but a full appreciation of Seurat will have to await further developments in the science of perception.

The desire of artists to produce strong visual effects with abstract figures is present throughout history. In early Islamic art, where representational figures were rigorously excluded from the mosques, striking geometrical structures were produced. Even black and white photographs in a book of some examples of Islamic art (see, for example, pages 179, 227, and 336 of ref. 14) seem to pop right out of the page. Traditional Japanese folk art abounds in optical art, especially the cotton summer kimonos (yukata) which make many currently popular optical dresses look pale in comparison. The abstract design motifs of ancient Mexico are optical art as are the Roman mosaic floors at Antioch. All of which proves the obvious, namely, that man has always been in possession of a magnificent scanning device (the eyeball), a fabulous selective light detector (the retina), and a fantastic interconnected digital computer (the brain). If optical art has an immediate appeal to the untutored eye so much the better. An innocent approaching a battle scene by Uccello, or first entering Chartres Cathedral or the Hall of Bulls at Lascaux (circa 15,000 B.C.,) cannot help but be overwhelmed. This does not exclude, however, the possibility of deriving much more from a work of art by careful study and analysis, but mere intellectualizing of a work of art is not sufficient to appreciate its beauty.

III. Techniques of Optical Art

To do justice to the multitude of techniques which optical artists consciously or unconsciously employ would fill a library. In order to render the discussion finite this cursory treatment has been confined to the problems of color and three-dimensionality and to the specific cases where optical components (other than those in the eye) are employed. Also considered are the artistic possibilities of the moiré technique since this is the medium in which I work. Moiré phenomena can help to explain many interesting visual effects and hence is of interest beyond that of a mere artistic medium.

A. Color

One of the most difficult and subtle problems which artists encounter is that of color. Leonardo da Vinci may be considered the founder of the art of abstract color. In his *Treatise on Painting*[15] he recognized the primacy of red, yellow, green, and blue. Leonardo appreciated that colors are influenced by their surroundings; thus, blue appears more pronounced near yellow, green near red, and so on. He further found that red light gives bluish shadows (shades of Land's two-color experiments!). Chevreul, a prominent nineteenth century French chemist and the manager of the Gobelin tapestry factory, in an effort to obtain good blacks became involved in a study of juxtaposed colors. His treatise on the subject[16] first published in 1835 provided a theoretical basis for the technique of the Impressionists and their immediate followers, notably Seurat. Seurat was a serious student of color theory, influenced by Maxwell and especially by the American, Rood.[17] Seurat used pure colors (the primaries and intermediate colors, mixed with white for luminosity), but never mixed colors.

Many of the contemporary optical artists utilize the juxtaposition of colors for heightened optical effects. A frequent color combination is blue and red (azyan and magenta is also particularly striking). In the *Responsive Eye* exhibit[5] the artists, Molinari, Anuszkiewicz, Liberman, Vasarely, Kelly, Stanczak, and Poons use the blue-red combination effectively. The red region immediately surrounding the blue is tinged with a deep red after-image which pulsates and makes for a lively appearance. Under strong illumination, such as usually encountered in a museum, the red appears forward and the blue recedes. This effect, well known to artists (see, for example, ref. 18), takes on an exceedingly dynamic and almost magical quality if the illumination is lowered. Apparently this phenomenon is due to the inability to focus simultaneously colors of the extreme ends of the spectrum with the nonachromatic lens of the eye (compare ref. 19, chap. 2 on this question). When the illumination is very low the blue takes on a phosphorescent quality and the red appears black, undoubtedly due to the shift of the spectral sensitivity of the eye to shorter wavelength for low illumination (the Purkinje phenomenon).

Subtle color differences are present in the work of Reinhardt; a painting by him consisting of squares of different nuances of red was shown at the *Responsive Eye* exhibit. He has produced a series of blue paintings in the same style. More remarkable are his black paintings (reminiscent of the style of the early abstractionist Rodchenko) which consist of barely perceptible black squares of slightly different reflectivity. Another artist in the quiescent mood is Albers whose more recent work consists of squares within squares each with a different, or only slightly different, color. Albers is a foremost experimenter in the art of color (he calls his studies a search—rather than research) and his book on the subject[20] is accompanied by a portfolio containing many interesting color abstractions produced by him and his students.

Color has an emotional aspect which most artists respond to deeply and which has not been defined precisely in psychological (let alone physical) terms. Thus, Kandinsky[10] writes of colored circles on a white background for which "yellow moves out from the center, blue moves in upon itself, red rings inwardly" and so on. He recommends yellow for sharp forms and blue for round forms. All this is highly personalized, and another painter may have quite the contrary opinion. The subjective approach to color reached its apex with the polemics of Goethe against the spectral theory of Newton. Despite the misunderstanding and the stubbornness of Goethe to appreciate correctly Newton's experiments, (see ref. 21, pp. 112–116) the former's influence still remains strong among some art teachers (e.g., ref. 18). Most experts on the physical and psychological aspects of color generally discard Goethe's acute, albeit bungled, observations: for example, in an otherwise excellent text on color by a physicist[22] no mention is made of Goethe. Recently a re-examination of Goethe's *Farbenlehre* has been undertaken[23] and Born has written a valuable analysis of the problem.[24] Color is more than the mere selective photochemical stimulation of nerve endings, and artists know this (see, for example, the interesting ideas of the contemporary French artist Lapicque[25]) as do psychologists (see, for example, the interesting symposium on color[26] in which both artists and psychologists participated). Lack of any rational basis for the phenomenon need not hinder the artist from using color effectively as long as he is prepared to experiment.

In a certain sense, color is a luxury. We do not use it for many of our informational needs. Black and white cinematography is a satisfactory means of communication, and some dreaming is in black and white. Black and white objects can be visually forceful especially if the black and white areas are equal. Many optical art pieces are in black and white (see, for example, Fig. 1) and need not suffer due to lack of color. As a matter of fact, subjective colors are seen in simple repetitive black and white structures.[27] A figure consisting of repetitive equispaced black and white lines shows a faint cross-hatch of yellow and blue reminiscent of the colors seen in Haitinger's brushes. Radiating black and white lines show a variety of fleeting color effects (mostly pink, green, and gold). Some of these effects are associated with moiré phenomena (see below) and are readily demonstrable with the moiré kit (see chap. 8 of ref. 28). Other effects may be due to the saccadic movement of the eyeball which, when scanning a black and white (and hence on-off) figure, results in the subjective color effects seen with stroboscopic flickering of about 20 cps (see ref. 29, Vol II, p. 255). The involuntary movements of the eyeball are mainly in the horizontal direction. As a consequence, optical art with predominately horizontal lines (e.g., the painting of Celentano in the *Responsive Eye* exhibit) takes on the character of a majestic sweep free of on-off interruptions.

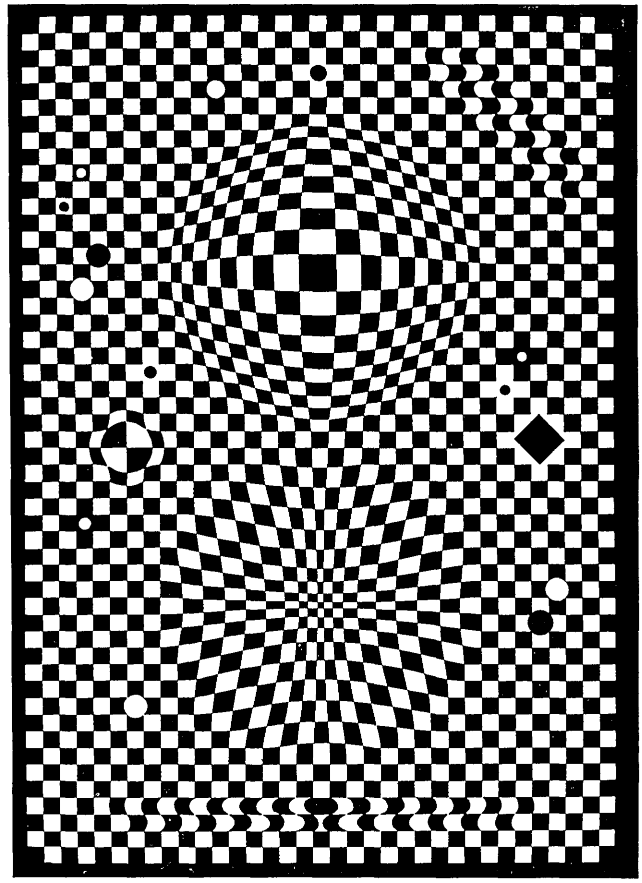

Fig. 1. "Metagalaxie" by V. Vasarely (courtesy of Pace Gallery, New York). This work has the aspect of an elastic checkerboard in which indentations, inflations, shears, and torsions have been applied.

B. Three-Dimensionality

Although beautifully decorative paintings (e.g., Persian miniatures and Byzantine icons) have been produced which are largely free of three-dimensional rendering devices, most artists throughout the ages have been searching for means of depth effects. To render depth to a flat canvas the artist must rely on monocular depth cues (or clues) of which the most common are perspective, interposition, and shadowing. These devices have been given considerable attention by perceptual psychologists (for a concise and modern account of the field of visual perception, see ref. 30). The rational use of perspective was codified in Renaissance Italy by Uccello, by della Francesca, and particularly by da Vinci.[15] Cézanne used perspective in an unorthodox way (see, for example, his "Card Players") to focus attention at the center of activity and thereby to obtain a more realistic visual effect than if he had adhered to the strict rules of perspective. Cubism, which one critic[12] has defined as "super-Cézannism", used many of the depth-rendering techniques of Cézanne to achieve a weightiness to objects. One also sees in the work of the Cubists, notably Picasso, double views of the same object reminiscent of a feature sometimes seen in Japanese prints. Surrealists such as Chirico and Dali have adopted perspective and shadowing depth cues to render their landscapes severely empty. The effect is heightened by the elimination of another depth cue, namely, that caused by the scattering of light by the atmosphere. Da Vinci's explanation[15] of why mountains in the distance look bluish and, indeed, why the sky is blue predates by three centuries the same explanation given by Tyndall.

Optical artists have used perspective (more specifically, foreshortening or orthographic projections) to achieve exciting visual effects. Examples of this in the *Responsive Eye* exhibit are the works by Cunningham, Steele, Benkert, and Riley. Cunningham's piece has the aspect of an intricate Japanese wood puzzle. The visual effect of the work of the other three artists which are in black and white is visually stimulating. They give a feeling of tension achieved by gradations of foreshortening similar to the effect when we (or any other creature with eyes) approach a "visual cliff" (see ref. 30, p. 48). The graded rotation of elements as seen in the work of Steele has an added feature of imparting a feeling of torsion. All of these aspects are contained in the work of Vasarely illustrated in Fig. 1. Riley has achieved three-dimensionality with families of curves (reproduced in a number of places including the back cover of refs. 5 and 28) of damped oscillation with increasing period. The line-width is varied (as foreshortening), but the principal three-dimensional effect is due to the lines being closer (an element of perspective present in contour maps) at regions corresponding to the approach to the valleys. This same kind of three-dimensional effect is seen in interferometric pictures of refractive index gradients (see, for example, ref. 31, p. 12).

There are, of course, a number of other depth devices used by artists over the centuries. One effective method of giving depth, or rather a floating feeling, is that used by Dorazio in the *Responsive Eye* exhibit: he overlays stripes of paint with translucent color.

C. Art with Optical Components

Experimental physicists are familiar with the beauty of images which can be obtained with lenses, mirrors, and polarizing elements. An atlas prepared by three French optical scientists[31] contains magnificent examples of such phenomena. It may be that physicists who chose optics as their specialty did so because of their innate sense of visual beauty. Huxley has remarked[32] that children may be divided into two categories—the visualizers who think in geometrical terms and the nonvisualizers who prefer algebra and imageless abstractions. Perhaps artists and optical scientists are from the former group. Many scientists will regard the pieces by le Parc in the *Responsive Eye* exhibit (distortion of lines by a curved mirror) and by Gerstner (distortions of concentric circles by a highly aberrating plastic lens), both of which are essentially the Ronchi test,[33] as scientific displays rather than art. These pieces as well as the photoelastic stress patterns by Gerstner are, nonetheless, beautiful even though they are familiar to scientists. Work of this kind is only original when it is presented in a visually interesting manner as a composition, such as in the piece by Gruppa N at the *Responsive Eye* exhibit (reflecting pipes on a linear background) or in the machine-turned metal array of Gerstner (Fig. 2). Arman has effectively used small shiny machine-parts, imbedded in plastic, to produce visually interesting compositions.

Optical artists have used repetitive lens elements to obtain certain visual effects, notably the aspect of motion. Isolated small lenses placed over some figure can produce interesting effects especially if the lenses are of different focal lengths. A lively piece by Bauermeister using this principle was shown in the *Responsive Eye* exhibit. Also at this exhibit the now well-known three-dimensional device of reticulated lenses (for a bibliography of this technique dating back to the experiments of G. Lippmann, see ref. 34) was used by Foyster to obtain motion (of red and blue dots) as well as depth. A more forceful use of lenticular ele-

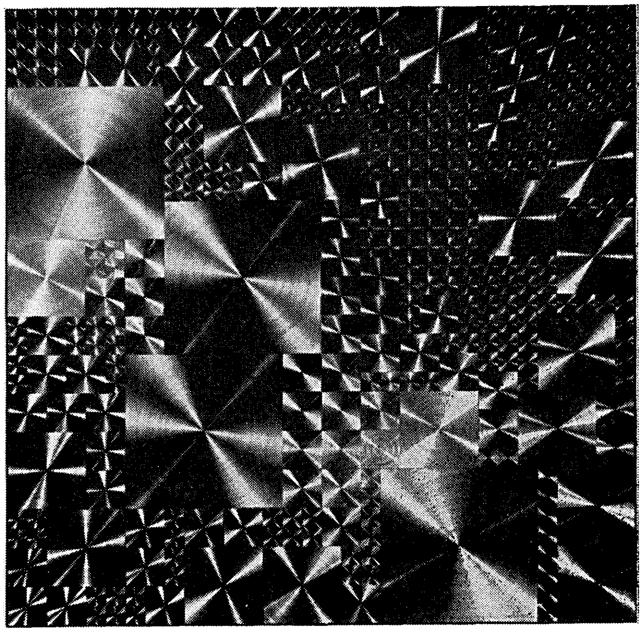

Fig. 2. "Texture Picture" by K. Gerstner (courtesy of Staempfli Gallery, New York). This is a composition of machine-turned metal squares.

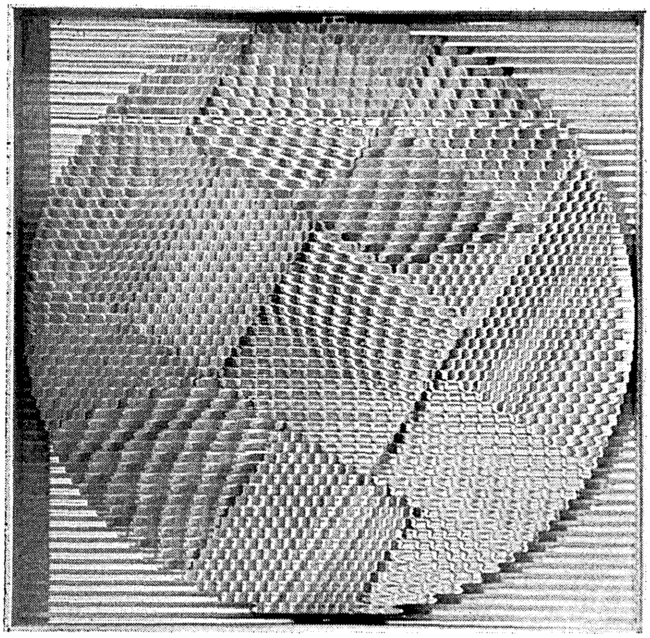

Fig. 3. "White Light Dynamo" by H. Mack (courtesy of Howard Wise Gallery). This piece consists of a corrugated material rotating behind a lenticular glass.

ments has been achieved by Mack whose piece illustrated in Fig. 3 consists of a coarse reticulated glass which overlays a corrugated material, the latter being rotated by a motor (and hence it is Kinetic Art). Mack has also used commercially available embossed metal products in original ways (e.g., his piece in the *Responsive Eye* exhibit) without the addition of lenses. Mack's recognition of the beauty of some artifacts of our industrial society is much in the Bauhaus tradition.

A forerunner of the lenticular lens technique is the vertical lath system developed by the artist Bois-Clair in 1692. Two distinct pictures are painted on a plane surface over which is fixed a rather close grid of vertical laths. From one side we see one picture and from the other another picture. This technique was utilized effectively with simple colored forms by Agam and by Cruz-Diez in the *Responsive Eye* exhibit. An attractive variant of this technique by Costa using twisted strips of white plastic on a colored background was also shown in the *Responsive Eye* exhibit.

The utilization of simple optical devices for the production of a work of art does not of itself make the piece trivial. The work of kinetic sculptors such as Calder, Rickey, and Lye (the latter uses involved programmed motion) could hardly be considered weak because it is based on Newtonian mechanical principles.

D. Moiré

The moiré phenomenon is based on the fact that, when two or more families of curves (actually of finite linewidth[35]) are superposed, a new pattern appears: the moiré. The moiré pattern which is the locus of points of intersection is, in principle, calculable[35–37] (see also the annotated bibliography, ref. 38). I have utilized the moiré technique in the constructions which were exhibited in my one-man show.[39] Many of the pieces consist of a plastic on which is silk-screened a family of curves precisely produced, the plane of which is separated some distance from another family of curves (or a family of distorted curves). The choice of distance determines both the moiré produced and the motion effect which is present. The moiré patterns in some of the pieces move wildly with a slight movement of the viewer. A static view of such a pattern is illustrated in Fig. 4. One piece (Fig. 5) is so sensitive that spots appear to float out in rhythm with the viewer's breathing (normally accompanied by slight forward and backward motion). In some of the constructions the figure looms larger the further away one views the object. This result is the opposite of conventional perspective and hence can give the viewer an unsettling feeling which, in the proper architectural environment, can be quite enjoyable, as mentioned in Sec. I. The movement of the moiré patterns is a consequence of changing projections and hence of varying points of intersection.[25]

More than two overlayed families of curves produce still further effects. The three-dimensional structures (prisms of sine curves) produce a variety of moiré patterns (for example, those of Fig. 6) which change (or even disappear) with varying distance and angle of observation. Combinations of such constructions produce even more bizarre effects. These prisms were also made in color, each face being a different color, to produce an almost limitless variety of different moiré patterns. Radial patterns in color (planes of three colors with black to enrich the color were used—the Bezold

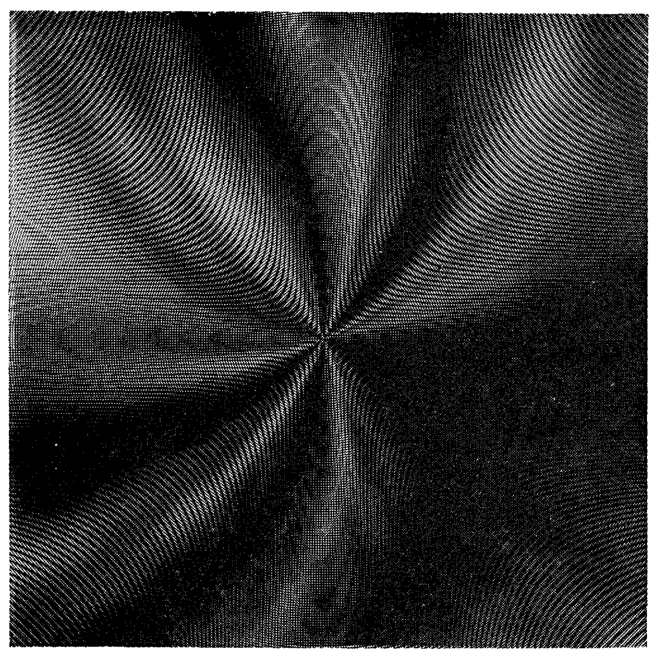

Fig. 4. "Double Equispaced Circles" by G. Oster (courtesy of Howard Wise Gallery). A moiré pattern of streamers appears when viewed off the perpendicular direction.

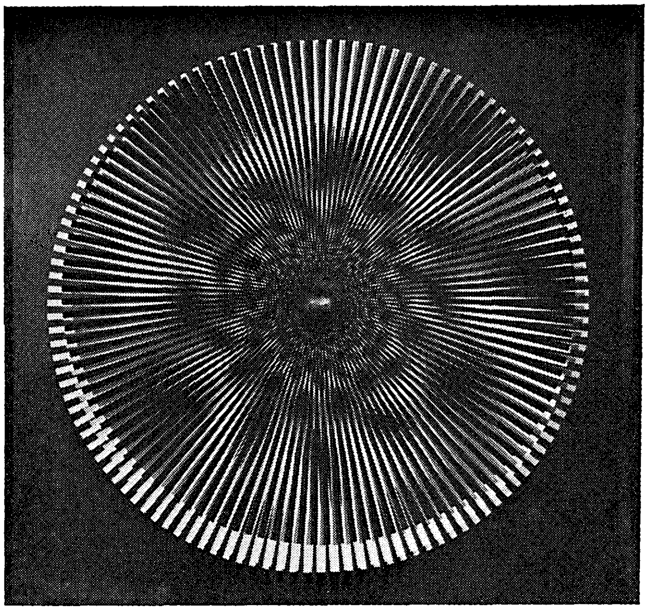

Fig. 5. "Triple Radial" by G. Oster (courtesy of Howard Wise Gallery). Three radial figures give a moiré pattern consisting of dots which appear to float out and twist with slight movement of the observer.

effect, see ref. 22, p. 181 and Plate XI) have an almost magical effect for the viewer as he moves about. Colors of undefined hues of varying saturation alternately loom large and small in an intricately winding pattern.

Currently I am exploring the artistic potentialities of moiré with curved surfaces and of programmed (including random) relative movements of the families of curves. Even in a static state moiré has many design possibilities, as illustrated in Fig. 7.

In the *Responsive Eye* exhibit moiré constructions made by Gego, Yvaral, Levinson, Wilding, Goodyear, Aliviani, Oster, and Sedgley (a painting) were shown. The range of the moiré technique is so broad that by this means one can produce pieces ranging from pyrotechnic to quiet depending on how it is employed.

One visual aspect of the moiré phenomenon is associated with the apparent break at the intersection when two lines cross at an angle smaller than about 45°: it is as if the two lines were twisted like wires at the intersection. This effect (related to the Poggendorf illusion) is probably the basis of many other optical illusions (see, for example, ref. 28, chap. 8). The artist, J. Soto, has produced constructions (see, for example, Fig. 8) based on this principle: a repetition of crossings. He suspends objects (for example, a stick the size of a pencil hanging by a thread) in front of a family of straight lines. By this and similar means he obtains lively and sometimes beautiful effects.

IV. Theory of Edges

Since prehistory artists have outlined figures, yet such lines should only be a mathematical fiction. Nevertheless, artists do see the edges of objects as lines; therefore the edge must have some perceptual reality. Prolonged examination under strong illumination of a sharp edge (for example, at the division between a well-defined black and white area) reveals a visually exciting phenomenon: the edge appears as a random (in time) series of sharp points (usually purplish) which are perpendicular to the edges and lie in the illuminated (or white) area. This effect could be due to the moiré pattern produced by the diffraction image of the edge and its slightly rotated superposed after-image. Parallel lines of graduated spacing produce V-like moirés with the apex perpendicular to the direction of the lines.[3,40] The diffraction image of an edge (usually seen under Fresnel conditions) is only vaguely perceived by the naked eye. The moiré pattern of the diffraction image with its superposed after-image (Fig. 9) is easy to see, but its presence is shortlived. The eye in its involuntary rapid sweeping motion (a necessity if images are to be retained[41]) undergoes some slight rotation.[42] Since the image is seen only at the end of the transit (the after-image is retained for a fraction of a second) conditions are right for producing a moiré pattern. It is significant that some of Cézanne's edges are serrated. This is not due to a coarse brush technique, but rather to his attempt at approximating the transient visual effects of an edge described above.

It has been suggested[43] that the remarkable textural effects obtained by viewing precisely drawn families of

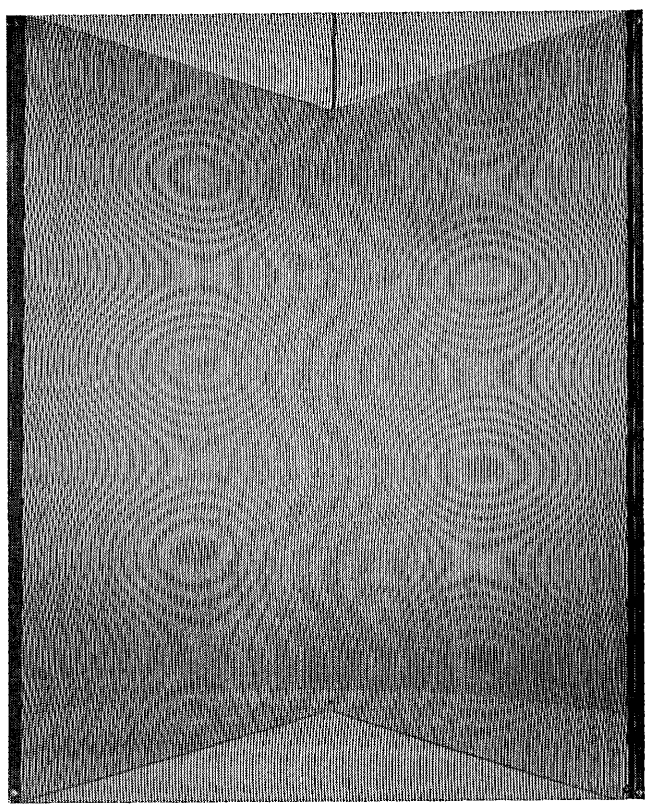

Fig. 6. "Sinusoidal Prism II" by G. Oster (courtesy of Howard Wise Gallery). A 60° rectangular prism of sinusoidal family of curves. The moiré pattern produced by two faces changes its character with the angle of observation.

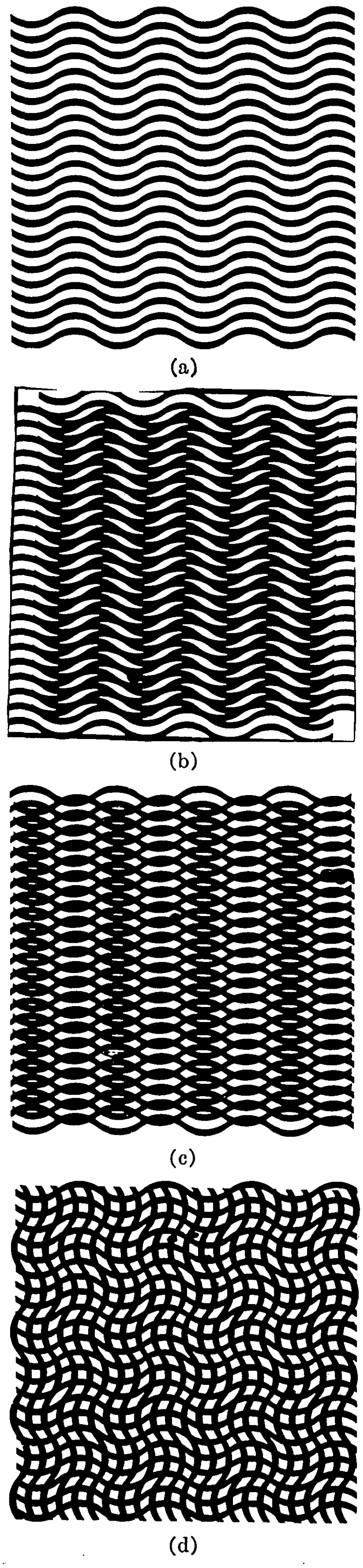

Fig. 7. Designs (moirés and autocorrellations) produced by overlapping the sinusoidal curves of (a). (b) and (c) are with orthogonal displacements. (d) is with 90° rotation.

lines is not due to a moiré effect since they are still present when the image is stabilized by the contact lens technique. The moiré phenomenon is extremely sensitive to slight movement, however, and if the contact lens slipped slightly on the cornea this would negate any attempts to stabilize the image. The moiré textural effect is the origin of some of the visual excitement of many examples of optical art.[28] This is particularly pronounced for Riley's paintings containing families of curves and can be exaggerated by rocking a reproduction of her piece back and forth. The pink color which is observed may be due to the greater persistence of the red component in the white portion of the after-image.

Moiré patterns may also be produced with the prolonged after-images obtained when viewing for a few seconds a well lit figure of parallel lines and then closing the eyes. The procedure is first to stare at the figure, then to rotate it, to stare again, and to close the eyes. The moiré pattern will appear as an after-image. Viewing with each eye alternately will not produce a moiré pattern, but only two overlapping figures (the grating in two orientations) are observed in the after-image. In line with this result, the stereoscopic viewing of two families of curves does not produce a moiré pattern since each image is recorded in separate portions of the brain.

The edge of a spherical object has a quite different aspect from that of a sharp edge. Here the light curves around the periphery in agreement with the mathematical treatment of inflection of waves by convex objects.[44] Again, Cézanne recognized this fact as shown by the appearance of the apples in his still lifes (for an eloquent description, see ref. 45). Shadows about objects may appear sharper than they really are. This arises from the Mach band effect[46] in which gradients of intensity are perceived as sharp lines where the second derivative of the spacial distribution of intensity is the greatest. This phenomenon has a neurophysiological basis.[47]

Nowhere are edges more dynamic than under the influence of LSD (lysergic acid diethylamide), a drug which heightens visual perception. Thus depth cues which are hardly noticed under normal conditions, such as two dots one of which is in focus and the other slightly out of focus, appear under LSD as being in different positions in depth. Color depth cues (forward and receding colors) also become much more apparent. I have carried out a number of visual experiments while under the influence of this psychedelic drug.[48] All the families of curves of my kit,[28] with the exception of the radial line figure, show effects akin to moiré patterns which are not seen under normal conditions. My conclusion is that, superposed on vision, is an out-of-focus figure consisting roughly of concentric circles; under heightened perception this screen is brought to the fore and hence one sees moiré effects when looking at regular structures. In the radial figure the lines are orthogonal to the lines of the hypothetical screen and therefore no new moiré pattern will be produced. The cones of the fovea are connected to individual nerve fibers which must course around and over the cones to reach the optic disk. This could provide the histological basis for the screen.

Nowhere in this discussion have we considered the dynamics of composition which is so important to the artist. ("The totality of a work of art is not the mere sum of its constituent parts.") Perceptual organization as it applies to art has been treated in detail.[49] This approach to visual problems has been largely dominated by the Gestalt psychologists (e.g., Koffka,[50] for a critical analysis, see ref. 51, Part II). Physicists may find that the terminology adopted by the Gestalt psychologists, namely, that of field physics, confusing when used in this context, and it is probably misapplied when attempting to explain the workings of the brain. The figures presented by the Gestalt psychologists (e.g., the figure–ground reversal for a staircase, the mental filling in of an incomplete square, etc.) are convincing demonstrations of the organizing tendency in perception, but they do not explain the process. Drawings of a wire cube have a three-dimensional aspect only when the view is for certain directions. It has been found that a correlation exists between the complexity of the drawing (of wire models of cubes and other solids) and its aspect of three-dimensionality.[52] The more complex figures contain a greater number of line crossings than do the simpler figures. As pointed out above, crossing lines have a visual excitement, and this could influence our choice of which figure appears more three dimensional than another. At the *Responsive Eye* exhibit a painting by Morellet, consisting of an elaborate figure of intersecting straight lines, illustrates this point. At the regions where there is the greatest number of crossing lines (and at small angles), there is the greatest amount of activity. These regions seem to jump out of the figure to give a spangling effect to the whole work. Also of relevance at the exhibit is the crossed thread construction of Fuller.

In representational painting the filling-in aspect may be made more by intellectualizing (and hence relying on experience) than by optical (and primitative neurological) stimulation. In a classical Chinese landscape, for example, the artist may give the feeling of fog in a mountain valley simply by adroitly outlining the peaks of the mountains and placing some sharply defined figure in the foreground. It is left for the viewer to fill in the rest of the picture. In this sense, optical art is not intellectual. One could imagine the construction of an optical scanning device having (a) the feedback mechanisms of the eye,[53] (b) the appropriate photocells and filters to match the spectral sensitivity of the eye, (c) a built-in delay circuit to correspond to after-image retention, and (d) a circuit to correspond to the local inhibitory responses of the neural system of the retina[47] which could match the responsive eye. We would still not, however, duplicate the emotional response which one achieves by viewing the best examples of optical art.

V. Art Without Optics

There is a storehouse of beautiful visions of optical art in the head. The fantastic highly geometrical figures one "sees" (not quite the appropriate word) with the eyes closed when we are in a relaxed state prior to falling off to sleep has been the subject of an extensive literature (e.g., ref. 54; for bibliography see ref. 55). These figures (our built-in geometry, so to speak), which seem to glow in the dark, are often referred to as phosphenes. Phosphenes are not to be confused with the prolonged after-images which interested the early physicists. Newton is reported (ref. 21, p. 158) to have stayed in the dark for three days to retain (he did!) the after-image of the sun. Phosphene phenomena have recently become of practical importance in connection with the hallucinatory effects one encounters under conditions of perceptual deprivation which astronauts undergo.[55]

Phosphene figures are of many forms and colors. One sees concentric circles, spirals, and radial patterns. On the cover of this November issue of *Applied Optics* is my interpretation of one figure which appears occasionally as a fleeting image. A pressure phosphene can be produced simply by closing the eyes and applying pressure with the fingers to the outer edges of both

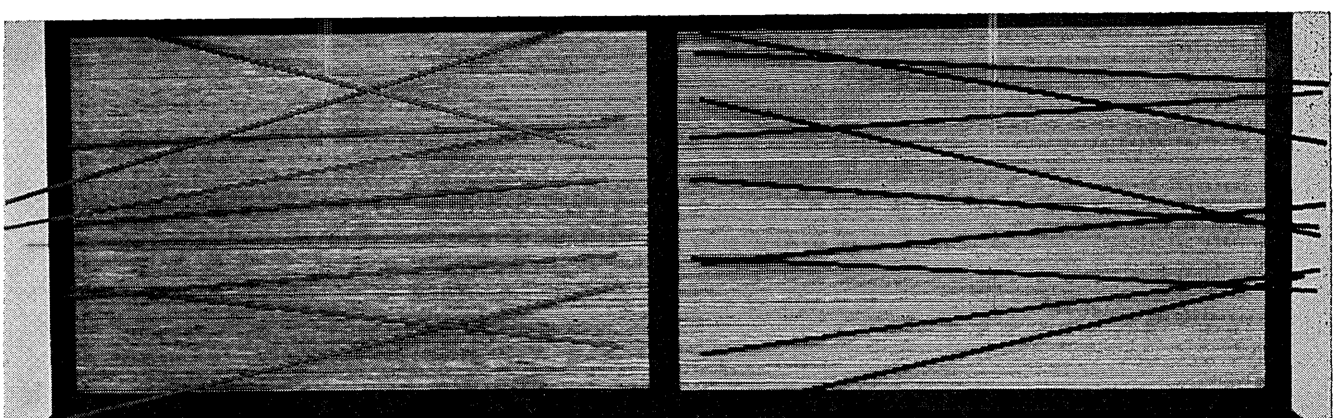

Fig. 8. "Baguettes Rouges et Noirs" by J. Soto (courtesy of Kootz Gallery). Rods at various angles suspended in front of parallel lines. The more inclined the rod the greater is the frequency of intersecting "break" points.

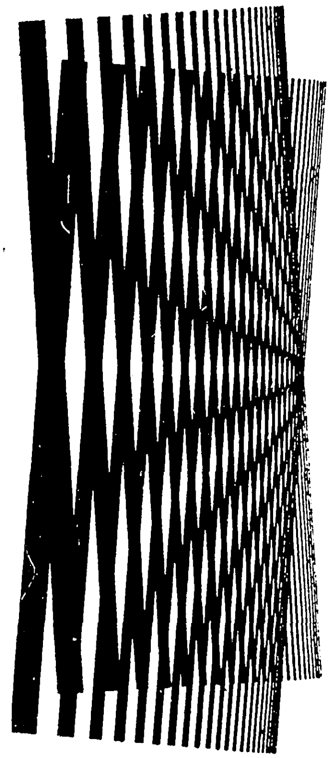

Fig. 9. Possible origin of apparent points on a vertical straight edge. Overlapping of two families of lines representing the diffraction for a vertical edge. One represents the immediate image and the other the rotated after-image. The apex of the moiré pattern produced is in a direction orthogonal to the edge.

eyes. Everyone obtains the same pattern; at first the field acquires a general whitish glow, then after about 3 sec a scintillating checkerboard design is obtained. I have tried to capture the feeling of phosphenes by using the moiré technique for the "Miniature" series in my one-man show.[39]

Phosphenes can also be produced by electrical means (the electrodes are applied to the head) as Franklin discovered. Volta, who spent a great deal of time in this pursuit, recognized that these electrically induced phosphenes occur only when the current is turned on or off. Stabilized phosphenes can be obtained by means of a low-frequency square-wave generator. The character of the pattern changes with different frequency of applied voltage.[56] The electrically induced phosphenes are more enhanced and subject to recall after a long period of time (months) if the subject had been under the influence of LSD during the electrical stimulation.[57] My experience has been[48] that the ordinary as well as the pressure-induced phosphenes are likewise more prominent when under the influence of this psychedelic drug. Such effects coupled with extrapolations by the imagination of the subject could account for some of the bizarre *visions* which have been reported by many persons who have taken the drug.[58]

Artists have another source of inspiration for their work. Julesz[59] at the Bell Telephone Laboratories has shown that depth perception need not depend on the presence of a recognizable form. Thus, depth is perceived when one views stereoscopically two computer-produced random dot patterns one of which is a copy of the other but with a portion slightly displaced. By this means one can produce a variety of three dimensionally appearing objects which need not occur in nature. In fact, by proper programming one should be able to produce with the digital computer, objects which lie beyond the imagination of even the most imaginative mathematicians such as Hilbert.[60] All this may have a terrifying aspect to most artists, but it is no worse than da Vinci's admonition to sixteenth century artists when introducing his treatment of the geometry of perspective,[15] "let no man who is not a mathematician read the elements of my work". Computer technology has far to go to duplicate the spirit and excitement of art. When such a day is reached, however, it will require an artist to do the programming.

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ICO PARIS
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Congress on Recent Progress in Optical Physics

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All persons who would like to attend the Congress are invited to inform the Secretariat as soon as possible.

Those who would like to give a paper should so indicate. Abstracts (250 words) with an estimate of the time necessary for a succinct presentation of the paper, should have been submitted before 30 September 1965 to the Organization Committee. No abstracts can be accepted after this date. The Organization Committee is notifying the authors before 15 November 1965 if their papers have been accepted for presentation. Final abstracts of the accepted papers should be sent to the Secretary of the Congress before 15 January 1966, in a form ready for photographic duplication. Rules concerning this preparation will be given in the circular to be sent to all intendant participants. **Seventh session of the International Commission Optics:** This session will take place during the Congress. The agenda and the time plan of the meetings will be subsequently communicated to the national committees. Attendance will be restricted due to the limited space available.

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