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Visual Spatial Illusions: A General Explanation

A wide range of visual illusions, including geometrical distortions, can be explained by a single principle.

R. H. Day

Under specified conditions a consistent discrepancy occurs between the apparent and physical value of a property of an object, such as its size, shape, orientation, or movement. These differences are called spatial illusions and for over a century one group, the geometrical illusions, has remained unexplained despite intensive experimental analysis. Although there has been a resurgence of interest in explaining these effects, such as attempts to do so in terms of spatial constancy (*1*, *2*), no theory has yet gained general acceptance. I wish here to propose a general explanation that encompasses a wide range of effects, including the geometrical distortions and the effects which belong in the same class but are not usually treated as illusions. Whereas the following explanation is based on the processes that normally maintain perceptual constancy, it is more general than others and recognizes separate classes of illusion for size, shape, orientation, and movement. All classes are linked to a particular spatial constancy and explained in terms of the same principle. Size illusions have been singled out for detailed treatment because, in addition to containing the Müller-Lyer (*3*) and most of the other well-known effects, their analysis serves to elucidate the main principle on which the general explanation is based. However, I emphasize that there are *separate classes* of illusion derived from independent manipulation of the stimuli that normally preserve a particular form of perceptual constancy. Also, there is a much wider range of visual constancies, including those of orientation and movement, than is generally recognized.

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Size Constancy and Distance Stimuli

As the distance of an object varies, the size of the retinal projection of the object (image), for all practical purposes, varies as an inverse linear function of distance (*4*). Departures from this function are slight as the object itself increases in size. Data show that with monocular viewing in a dark, featureless environment the apparent size of an object also varies as an inverse linear function of distance (*5*). However, with binocular vision in a normally illuminated, structured environment the apparent size of an object is nearly constant with distance. This relative stability, first described by Descartes (*6*) and studied quantitatively by Martius (*7*) and Thouless (*8*), occurs even when the observer and object are separated by more than 1000 meters (*9*). Because the retinal image of an object varies with distance but the apparent size remains constant, it has been assumed that size constancy is dependent on sensory information for distance. This assumption was tested and confirmed by Holway and Boring (*10*) in a well-known experiment in which information for distance was progressively eliminated until apparent size approached that predicted from changes in the retinal image.

Information for distance is conveyed by a wide range of stimuli traditionally called "cues for distance" (*11*). Whereas there is no absolutely correct or universally accepted classification of these distance stimuli, they can be arbitrarily but conveniently grouped into five categories: (i) retinal disparity (or binocular parallax), (ii) muscular adjustments (convergence, accommodation, pupillary change), (iii) monocular movement parallax, (iv) atmospheric stimuli (color change, aerial perspective), and (v) projected stimuli (linear perspective, texture gradient, element size, interspace size, element frequency, interspace frequency, overlay, and elevation), all of which derive from the projection of three dimensions onto two at the eye (*12*). This list may not be exhaustive but it includes most of the binocular and monocular stimuli known to be involved in discrimination of distance. The different classes of stimuli and those within a single class can be independently eliminated or varied. For example, retinal disparity, a binocular stimulus derived from the slightly different image at each retina, can be eliminated by using one eye and can be varied by means of an optical system (*13*); adjustments to the optics results in disparities greater or less than normal for a given distance. The observation that at least five groups of stimuli convey information for distance, that they can operate as distance stimuli alone or together, and that each can be varied with the image of the object not varied, are central to the following explanation.

Apparent size and apparent distance are by no means perfectly correlated. A substantial body of data (*14*) has shown that apparent size cannot be accurately predicted from apparent distance data and that the hypothesis of apparent size–apparent distance invariance is not acceptable (*15*).

Size Illusions and Distance Stimuli

Distance stimuli serve to maintain constancy of apparent size as the retinal image varies with the distance of the object. It follows that if the stimuli which normally preserve constancy are independently manipulated, with the image of the object not varied, changes in apparent size will be induced. The differences between apparent and physical size are called spatial illusions and occur when retinal disparity, convergence-accommodation, and projected distance stimuli (elevation, perspective-texture, element and interspace frequency, and element and interspace size) are singly or jointly varied. Furthermore, they can be predicted when other distance stimuli are similarly manipulated.

Gogel, Wist, and Harker (*16*) varied retinal disparity by optically modifying interpupillary distance, with the distance of the object constant at 152.4 centimeters. Convergence and accommodation were controlled throughout and alternative distance stimuli were eliminated. For the three interpupillary bases (12.4, 6.5, and 3.2 cm), which represent approximately doubled, normal, and halved ocular separations, the apparent size of a 30.5-cm object was 28.5, 31.9, and 40.0 cm, respectively. Thus with increased disparity equivalent to that for a smaller distance, apparent size decreased (28.5 cm) and with reduced disparity it increased (40.0 cm). With normal disparity there was a close correspondence between apparent (31.9 cm) and physical (30.5 cm) size. It can be concluded that independent manipulation of the disparity stimulus for distance, with the image not varied, results in discrepancies between apparent and physical size, that is, in size illusions.

Early (*17*) and recent (*18, 19*) experiments involving manipulation of convergence and accommodation by optical and other means have also produced differences between apparent and physical size. Leibowitz and Moore (*19*) took steps to preserve the normal

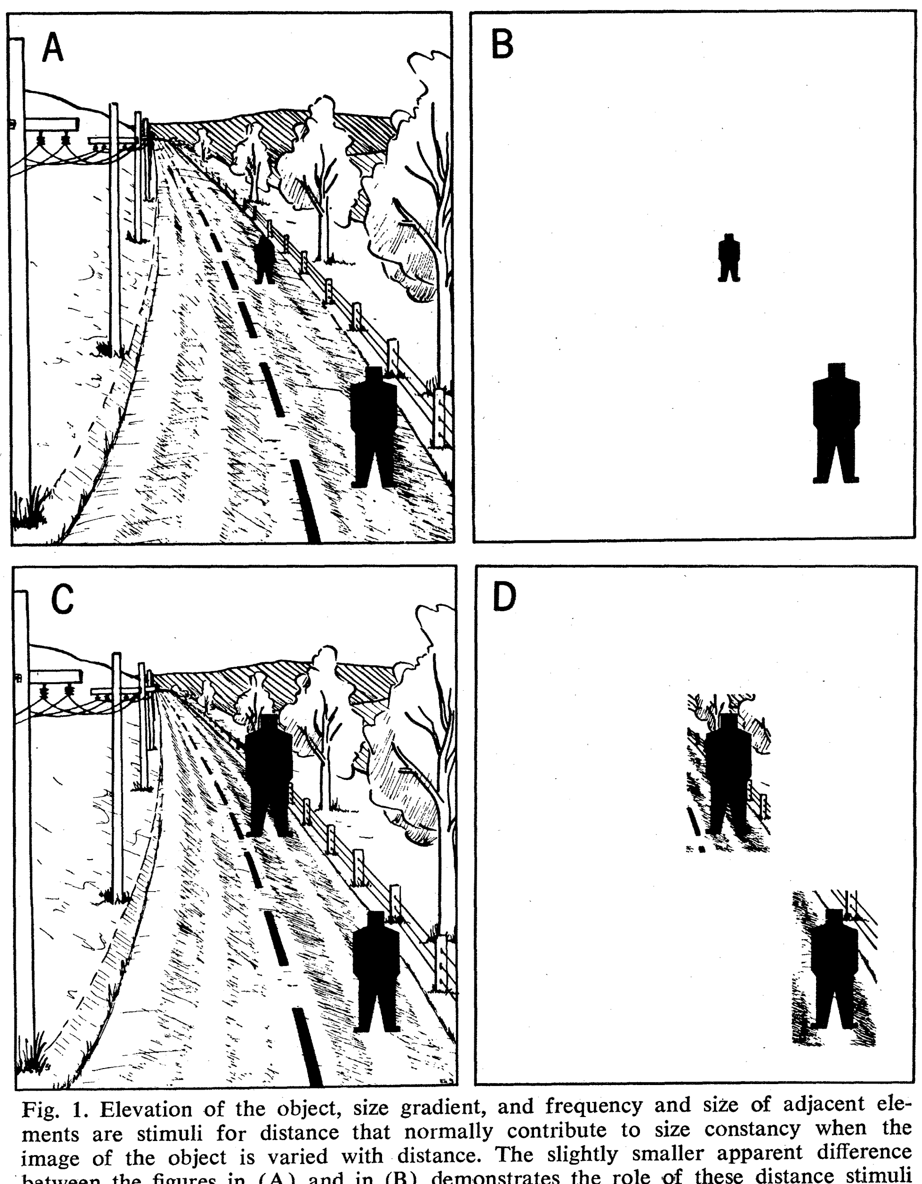

Fig. 1. Elevation of the object, size gradient, and frequency and size of adjacent elements are stimuli for distance that normally contribute to size constancy when the image of the object is varied with distance. The slightly smaller apparent difference between the figures in (A) and in (B) demonstrates the role of these distance stimuli in preserving size constancy. Size illusions occur when figures and their images are not varied, and the same distance stimuli are varied, as shown in (C) and (D).

correspondence between convergence and accommodation, an oversight of many earlier studies, and obtained size matches to a standard object at five observation distances (10, 25, 50, 100, and 400 cm). At each distance accommodation was optically adjusted to .25, .50, 1.00, 2.00, and 3.00 diopters with convergence individually adjusted to correspond. Apparent size varied with convergence-accommodation following a linear function up to a viewing distance of about 100 cm. The differences between apparent and physical size are spatial illusions induced by independent variation of muscular stimuli for distance.

Projected stimuli, including overlay, elevation, size gradient, element size, and element frequency serve to maintain a degree of size constancy even in a picture (Fig. 1, A and B) (*20*). The difference between the "near" and "far" objects in Fig. 1A with distance stimuli present is less than in Fig. 1B in which the stimuli are absent. Size illusions occur when these same stimuli are varied either singly or in various combinations, with the image of the object not varied. An example of a size illusion from elevation, gradient, and element size and frequency is shown in Fig. 1C. In Fig. 1D the illusion persists after the complete gradient is removed so that only element size, frequency, and elevation remain.

McDonald and O'Hara (*21*) varied the elevation stimulus using a method developed earlier by Gibson (*12*). One object was mounted above a patterned surface, with the mounting concealed; with monocular observation the raised object, which was nearer, appeared farther away than a second located on the surface. The mean apparent size of the elevated object at a distance of 3 m was 37.1 cm, but another of identical size, located on the surface at the same distance, was 30.0 cm. That is, when the elevation of an object in the visual field is adjusted by raising it vertically to the same elevation as a more distant object, the size of the nearer object appears greater.

The role of projected size gradients from extended patterned and textured terrain as a stimulus for distance has been thoroughly studied by Gibson (*12*). The part played by the size of individual elements has been demonstrated by early investigators (*3*, *13*) and by Coltheart (*22*) and Landauer and Epstein (*23*). The greater frequency of elements per unit of visual angle that are projected from far areas of the terrain has not been considered as a stimulus for distance, although their variation with distance is obvious.

Blessing, Landauer, and Coltheart (*24*) varied size gradient and element size and frequency using two tunnels, each 450 cm long, but tapered and patterned to project stimuli equivalent to those from a 675-cm and a 225-cm tunnel. In the "longer" tunnel the apparent size of a 16.4-cm standard was 21.38 cm and in the "shorter" tunnel it was 16.38 cm. Under the conditions reported, accommodation and convergence would have been operative but constant and presumably would have been adjusted to the physical distance of the objects. Nevertheless, manipulation of the projected stimuli produced marked change in the apparent size of an object, the image of which at the eye was not varied.

Geometrical Size Illusions

For the most part the well-known geometrical size illusions derive from manipulation of one or more projected stimuli for distance, with the image of the focal object, usually a line figure, not varied (see Fig. 1, C and D). Typically the size of a single, adjacent, or attached element or the size or frequency of proximal elements is varied. In some figures the interspaces between elements or between the object and an adjacent element are manipulated; these interspaces also vary with distance under normal conditions. Examples, some of which are well-known illusions, others of which are simply derived from the principles described, are shown in Fig. 2. Failure satisfactorily to explain these geometrical illusions so far seems to have been due mainly to a failure to recognize the range and subtlety of the distance stimuli projected from the three-dimensional extended environment. Whereas the possible role of the size gradient in the form of perspective has been widely discussed (*1*, *2*), little or no attention has been paid to the size and frequency of adjacent elements and their interspaces, or to the elevation.

It can be assumed that the slightness of the effects in Fig. 2 are due in part to the presence of alternative stimuli, such as retinal disparity and convergence-accommodation, which signal the true distance of the objects. In this regard, Schlosberg (*25*) has argued that whereas any picture contains a number of stimuli for depth, such as shading, clearness of outline, perspective, and overlay, it also presents a number of stimuli for "flatness," such as identity of binocular images, absence of monocular parallax, and constant convergence and accommodation. Elimination of these stimuli for flatness would presumably increase apparent depth and, therefore, apparent size. However, I emphasize again that apparent size and apparent distance are not perfectly correlated (*14*, *15*). However, if alternative stimuli for true distance were eliminated and careful psychophysical procedures adopted it is conceivable that discriminable differences would occur between the pairs in Fig. 2. Greg-

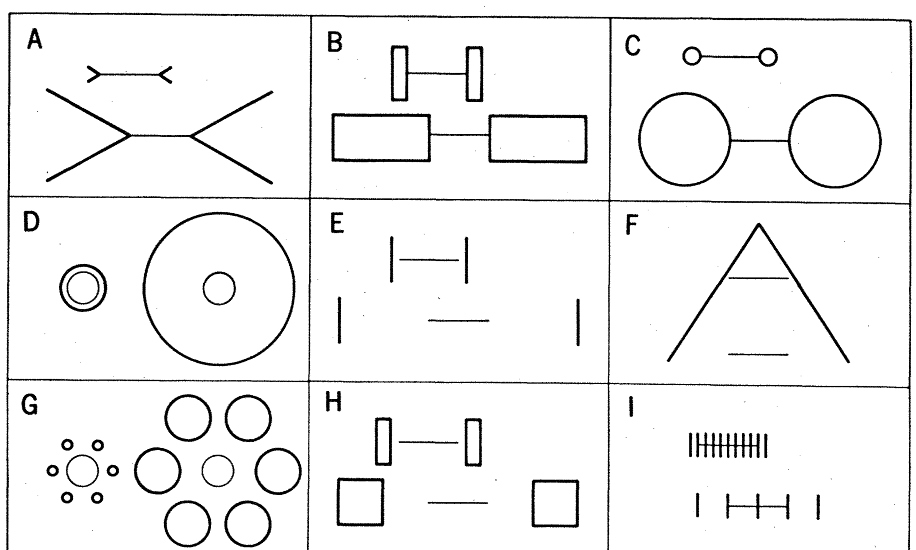

Fig. 2. Size illusions induced by the size of proximal elements (A–C), size of interspaces (D and E), size of interspace and presence of a size gradient (F), size of both elements and interspaces (G and H), and frequency of elements and size of interspace (I), with the image of the object not varied in each case.

ory (*26*) found such differences in apparent distance using luminous figures in darkness; a condition that would have eliminated some stimuli for the true distance of the figures.

Although tempting, it is not necessary to assume that the attached adjacent elements and interspaces of Fig. 2 induce neural processes which mediate size illusions. Whereas, undoubtedly, illusory phenomena are correlated with neural events and interactions between them, it is sufficient to account for the effects in terms of stimuli that are normally involved in the preservation of perceptual size constancy. Element and interspace size are merely examples of such stimuli.

Holway and Boring (*10*) showed that as the distance stimuli are progressively eliminated with the image varied, apparent size shifts from almost perfect constancy to that predicted by the visual angle of the external object. In other words, the degree of size constancy is a function of the number of distance stimuli operating. It follows that when the image of an object is not varied, the magnitude of the illusion will increase with the number of stimuli for distance. Leibowitz and co-workers (*27*) systematically varied the number of distance stimuli using actual scenes, photographs, and figures and convincingly showed that the Ponzo illusion (Fig. 2F) increases as a function of the number of distance stimuli available when the image of an object is not varied.

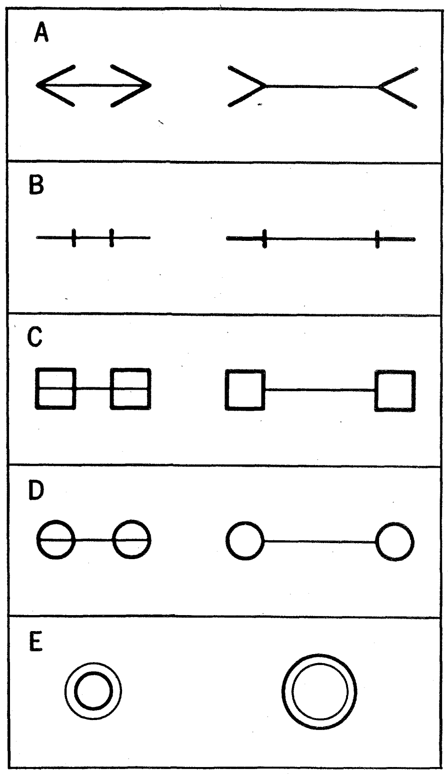

Fig. 3. Four versions of the Müller-Lyer illusion (A–D) in which the apparent size of the object (line) varies with the size of the adjacent elements (right) and size of the inner space defined by the elements (left). The Delboeuf illusion (E) is essentially similar with the size of the interspace determining the effect on the right, and the inner space determining it on the left.

Müller-Lyer Illusions

The Müller-Lyer illusions (Fig. 3) belong with those of Fig. 2, but more detailed attention to them is warranted by the considerable interest that they have aroused since they were originally described nearly a century ago (*28*). Two points, both sources of considerable misunderstanding, deserve emphasis. (i) The common version of the Müller-Lyer illusion (Fig. 3A) consists of two equal lines, one with outward arrows (the "long" figure) and the other with inward arrows (the "short" figure). However, a wide range of terminal elements in addition to the traditional arrows, including circles, squares, and straight lines coextensive with the main lines, results in an illusion (*3*, *13*) (Fig. 3). Therefore, an explanation applicable only to the illusion with the arrow attachments (*2*) is inadequate. (ii) It has been established, but not widely recognized, that the illusion with outward-directed attachments is 3 to 4 times greater than that with inward-directed elements (*29*, *30*). In fact, the illusion in the latter figure is sometimes absent altogether (*31*). As with some patterns (Fig. 2, A, B, and C) the basis of the illusions in the long component of the Müller-Lyer group is the size of the proximal elements. When the circles, squares, arrows, and lines (Fig. 3) are small relative to the main line the latter appears larger than a comparison line, and when they are large relative to the main line, the line appears smaller. Lewis (*32*) showed that when the attachments are coextensive lines (Fig. 3B) the illusion reverses when the two attachments are each about one third the length of the main line. However, with the typical arrow attachments, reversal from that which appeared larger to that which appeared smaller than a comparison line did not occur, although the trend was clear, and reversal would probably have occurred had the attachments been sufficiently extended. A similar reversal occurs with the Delboeuf illusion (Fig. 2D) as the outer circle, which defines the interspace between the inner and the outer circles, increases (*33*); it is reasonable to assume that this would be so with the other illusions of Fig. 2. It can be concluded that the basis of the long versions of the Müller-Lyer is the size of the attached elements and that they belong in the same class as the other illusions in Fig. 2 in which the horizontal line appears longer. When the inward-directed arrows of the short illusion are placed at a distance from the ends of the line, the illusion reverses. Fellows (*34*) demonstrated that with this modification it is the interspace between the arrows and the ends of the line which determines the illusion (Fig. 2, D–F).

Erlebacher and Sekuler (*30*, *35*) have shown that the basis of the Müller-Lyer illusion with inward-directed arrow attachments (Fig. 3A) is the distance between the ends of the obliques, that is, the defined spaces between the ends of the arrows. It seems reasonable to assume that all the short components of the Müller-Lyer group (Fig. 3, B–D) and the smaller component of the Delboeuf figure (Fig. 3E) are determined by the defined inner space.

In summary, the long and short components of the Müller-Lyer illusions, including those with arrow attachments, are probably separate illusions; the first is determined by the size of the attachments and is reversed when they are large, and the second is determined by the inner space defined by the inward attachments (*35*). Both can be satisfactorily accounted for in the terms set out here; the size of the attachments in the long component and of the defined inner space between attachments in the short component are essentially distance stimuli that under normal visual conditions assist in the preservation of size constancy. Thus, the Müller-Lyer group is essentially similar to other illusions in which the size of adjacent elements is the principal determinant of the effect. Since it is the size of adjacent elements and spaces rather than the perspective effect of the arrow forms, attempts, such as that by Fisher (*36*), to test a constancy theory based on the latter assumption have not been successful.

Orientation and Movement Illusions

Apparent orientation, movement, and shape (in addition to size) exhibit considerable constancy when the orientation, movement, and shape of the image vary as a result of the tilt, motion, and bearing of the observer, respectively (*37*). Consideration of orientation and movement constancy and their associated illusions will point to the generality of the explanation.

When the head of the observer is tilted laterally in a well-illuminated environment apparent orientation is perfectly constant (*38*), and in darkness it is nearly so (*39*). Orientation constancy depends on information for the orientation of the observer and this is conveyed by both gravitational and visual stimuli. Elimination or reduction of these stimuli reduces orientation constancy considerably (*39*, *40*). If gravitational and visual stimuli for the orientation of the observer are separately varied, with orientation of the image at the eye not varied, a difference occurs between the apparent and physical orientation of the object. The gravitational stimulus can be changed by rotating the observer in the darkened cabin of a human centrifuge (*41*, *42*). Rotation imposes a gravitoinertial force, the direction of which is a function of centripetal and gravitational directions. Under these conditions a vertical bar appears tilted, an effect called the oculogravic illusion. Visual orientation stimuli, which derive from environmental features and contours (analogous to projected visual stimuli for distance), can be changed by tilting the whole or part of the visual field (*43*). The Zöllner illusion, the apparent tilt of vertical lines by the superimposition of slanted lines, and its numerous variants (*3*, *37*) are instances of orientation illusions that occur when only that part of the visual field immediately adjacent to the object is tilted (see Fig. 4). Because the geometrical orientation illusions (Fig. 4) result from manipulation of visual stimuli for the orientation of the observer, it is necessary to distinguish them from geometrical size illusions that derive from distance stimuli. The two are often confused and explanations of size illusions have been unjustifiably criticized because they cannot account for orientation effects (*44*, *45*).

When the head is moved the retinal image of a stationary or moving object varies but the apparent motion of the object (including in the limit its stationary position) is extraordinarily constant (*46*). It is reasonable to assume that visual motion constancy, including constancy of the stationary position (usually called position constancy), is dependent on information for the movement of the observer. This information is probably carried by stimuli acting on semicircular canal mechanisms and by visual stimuli. Independent variation of these two classes with the visual image stationary gives rise to movement illusions. For example, if the stimulus for movement that normally impinges on labyrinthine receptors is varied by rotating the observer in a dark centrifuge, with a point of light stationary relative to him, the point exhibits apparent movement during acceleration, an effect called the oculogyral illusion (*39*, *42*). Likewise, if the normally stationary visual field stimuli for the movement of the observer are varied by moving whole or part of the field, the well-known illusion called induced movement occurs (*47*).

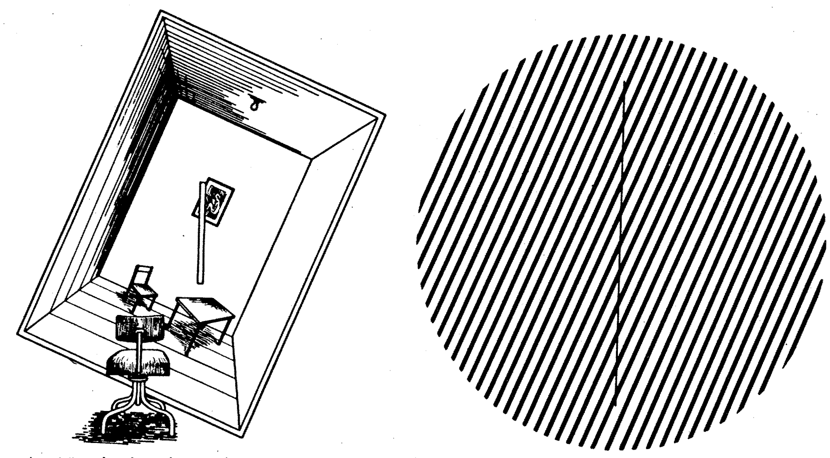

Fig. 4. Vertical orientation of the visual field and elements within it are stimuli that normally contribute to orientation constancy when orientation of the image is varied with the tilt of the observer. Orientation illusions occur when orientation of whole or part of the field is varied with image orientation at the retina not varied. In both figures the effect is greatest when they are held near to the eye to eliminate contours of the page.

It can be assumed that, as with apparent size and distance, correlations between the orientation of the apparent object and the body and between the movement of the apparent object and the body are not perfect.

Effects of Age, Practice, and Culture

An explanation of spatial illusions is incomplete if it cannot offer an account of the systematic change in the magnitude of some illusions with age (*48*), repeated judgments (the practice effect) (*49*), and cultural background (*50*). There is now a considerable literature dealing with each of these variables, and it is known that with age some illusions increase in magnitude and others decrease. It is reasonable to assume that these variations in magnitude are an outcome of change in those stimuli primarily involved in the maintenance of the associated perceptual constancy. For example, if during development there is, for whatever reason, a shift from motion parallax to projected stimuli in the maintenance of size constancy, geometrical size illusions that derive from the latter would be expected to increase and those from the former decrease. That is, if a particular stimulus at a certain stage of development assumes greater significance in the preservation of constancy its independent manipulation will have a greater effect in generating illusory effects when the image of an object is not varied. Conversely, if a stimulus progressively loses its significance in maintaining perceptual constancy the illusory effect from its manipulation would be expected gradually to decline. During repeated judgments of an illusory pattern similar shifts in the significance of stimuli may be expected to occur. It is reasonable to expect also that different stimuli are primarily involved in the maintenance of constancy according to the culture in which the individual is reared. Thus, manipulation of those stimuli would be expected to have a greater effect in causing illusions. In general it can be expected that those stimuli that are primarily involved in the maintenance of a perceptual constancy will, when varied with the image of the object fixed, give rise to the greatest illusory effects.

Summary and Conclusions

Representation at the visual receptors of such properties of the object as its size, shape, orientation, and movement undergo considerable variation as the distance, bearing, posture, and motion of the observer, relative to the object, changes. However, despite these gross and frequent deformations of the image, perceived properties remain extraordinarily stable. Such constancy has obvious biological utility; the observer perceives his world according to its fixed physical features rather than in terms of its variable sensory representation.

Constancy of apparent size, shape, orientation, and movement is dependent on information for the distance, bearing, lateral tilt, and movement of the observer, respectively. Thus, as the retinal image shrinks with distance, constancy of apparent size is maintained by five classes of distance stimuli that operate singly or in various combinations. Likewise, visual orientation constancy is dependent on gravitational and visual stimuli for the orientation of the observer, and movement constancy on visual and nonvisual stimuli for the movement of the observer. Illusions occur when stimuli that normally preserve constancy are operative but with the image of the object not varied. Thus if retinal disparity, convergence-accommodation, projected stimuli, or other distance stimuli are varied with the image not varied, illusions of size occur. Those resulting from variation of projected stimuli are the well-known geometrical size illusions and include the Müller-Lyer group. In essentially the same manner, independent manipulation of stimuli for the orientation and the motion of the observer, with the orientation and the motion of the image at the retina not varied, gives rise to illusory orientations and movements of the object.

Limited attempts to explain size illusions in terms of the projected stimuli that preserve perceptual constancy are by no means new; Thiéry (*51*) proposed such a view in the latter part of the last century, and in recent times there has been a spate of such proposals including the "misapplied constancy hypothesis" advanced by Gregory (*2*). However, Gregory's theory is confined largely to geometrical size illusions and invokes only distance scaling given by a limited number of projected stimuli. Furthermore, the Müller-Lyer illusion is seen by him to be a consequence of distance scaling resulting from the converging arrows. There is no recognition of the range of such effects with various attached elements, as shown in Fig. 3, and no attention is accorded the recently established difference between the illusions with inward- and outward-directed elements.

The theory of spatial illusions outlined here distinguishes between classes of illusory effect and, in linking each to its particular class of spatial constancy, offers a general and testable explanation. Failure to recognize classes of illusion (and perceptual constancy), such as those of size, orientation, and movement, can be regarded as among the major deficiencies of recent attempts (*2*, *44*) to explain illusory effects. I do not claim that this explanation, which I call the general constancy theory, satisfactorily encompasses all known illusions, but merely that it is more comprehensive than alternative explanations. I conclude that any stimulus which serves to maintain perceptual constancy of a property of an object as the visual representation of that property varies will, when independently manipulated with the retinal image not varied, produce an illusion. This general principle predicts the conditions under which illusory effects will occur and has wide explanatory application.

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6. "It is not the absolute size of images (on the eyes) that counts. Clearly they are a hundred times bigger (in area) when objects are very close than when they are ten times further away; but they do not make us see the objects a hundred times bigger; on the contrary, they seem almost the same size, at any rate as we are not deceived by too great a distance." (Rene Descartes, *Dioptrics*, 1637).
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11. Historically it was assumed that because only points and patches of light are projected at the retina, the third dimension, that of depth or distance, must be constructed from these data. However, retinal disparity, motion parallax, and geometrical features result in an immediate sense of depth and can be regarded as stimuli for depth in the same way as wavelength is a stimulus for color. The term "cue" wrongly implies a "criterion" or "sign" from which distance is derived rather than a stimulus. For this reason the term "stimulus for distance" is used.
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52. I thank V. Kohout and G. Swinton for assistance with illustrations and photography.