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CURRENT PROBLEMS IN RESEARCH

The Visual Space Sense

Empirical factors interacting with innate sensory processes lead to a stable spatial localization.

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The visual (or optical) space sense must occupy a dominant place in any well-rounded study of the physiology of vision. Visual appreciation of one's surroundings is the ultimate goal to which all of the anatomic and physiologic processes of the ocular organs lead. But research into the optical space sense, like other studies in sensory perception, is basically difficult because the final event in the chain from the retina to the brain is a psychic experience. The transition from the excitations in the cortex to the subjective experience defies explanation. This psychic experience is a private phenomenon and in itself is not subject to experimentation. Its properties, especially its mensurational aspects, can only be inferred from the nature of the responses (a form of behavior) to controlled optical stimuli. Furthermore, these responses are very likely to be modified by influences seemingly unrelated to the optical stimuli themselves.

The central problem in understanding visual spatial localization stems from the fact that the optical images falling on the retinas are essentially flat, or two-dimensional. All the *immediate* information about objects surrounding us that is obtained through vision alone must be contained within the patterns of those images. What are the processes (anatomic, physiologic, and psychologic) through which we become aware of the three-dimensional world about us, and through which we come to appreciate the spatial localization and orientation of objects in this three-dimensional world? By what means can we be sure the perceived space is indeed correlated with the objective space—the problem of veridicality—so that we may act effectively in this world of objects? Answers to these questions are important to our understanding not only of human perception in general but also of the processes involved in learning and in behavior.

In spite of all that has been written, and of all the experiments that have been devised to elucidate the central problem, there is yet to emerge a theory that is entirely satisfying, one that seems to fit the principle of scientific parsimony and having veridical and predictive value.

Two Approaches

Scientists interested in visual spatial localization are in one sense divided into two groups according to the goals that determine the approaches taken in their studies. Those in the first group simply correlate qualities of perceptual responses to specific changes in objective space, both the response and the stimulus being considered "objective" facts. Those in this group are basically and entirely unconcerned in any way with the eyes themselves, the intervening optics, or the physiology of the visual processes. They seek, however, relationships and quantitative predictive values from these correlations. This procedure has been highly productive and, of course, is the basis of psychophysics. The investigators in the second group, though in many cases they perform experiments and make analyses that are essentially the same (at least in part) as those of the first group, are not satisfied with this procedure alone. They seek to discover the underlying physical, physiologic, and psychologic processes upon which the emergence of specific subjective responses to controlled stimuli depends. The designs of their experiments usually reflect this goal.

The members of the first group have the advantage, for theirs is a functional approach and they can be unconcerned with such problems as whether there are or are not eye movements. From their studies have come well-known hypotheses, such as those of the gestalt workers, of aftereffects, of spatial adaptation, of the existence of a metric for visual space, and so on. These studies often make the task of the visual physiologist most difficult. He must try to account for the results and provide a basis for the hypotheses in terms of the optics, anatomy, and physiology of the visual processes. In some most important aspects this work has remained impossible—or at least its results are inconclusive—on the basis of our present knowledge.

Although considered somewhat unimportant for the last half century, the old controversy between nativism and empiricism, perhaps now in new clothing, has more recently re-emerged. In part this has been due to a revival of broad interest in perception in general, with many behavioral studies now being made (especially with the young, both animal and human), such as studies on imprinting and learning, on the effects of brain extirpation upon retention and visual discrimination, and on electro-

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physiologic characteristics, with imbedded electrodes. Instead of providing evidence in favor of one or the other of these points of view, these researches show more than ever that both are inseparably involved in a very complicated way in human visual perception.

Basic Phenomena

We may recall that there are three phenomena that are basic to our theories of visual space perception—(i) the differentiation of the figure from the background, (ii) the perception of relative visual direction, and (iii) the sense of externalization of perceived objects.

The first, discrimination of figure from background, must depend upon the contrast-light discrimination and the separation of contours.

The second, discrimination of visual direction, must occur by virtue of the retinal mosaic of the separated and isolated retinal receptors, each of which provides a visual response (a local sign) that can be differentiated from that of other receptors in the mosaic. Resolving power, the basis of visual acuity, is the least perceptible difference in direction referable to the angular subtense of images at the retina. The principal visual direction, arising from the receptors stimulated by the fixation point, and the sensitive subjective sense of the vertical, probably arising in some way from the gravity receptors of the body, establish a framework of relative visual directions by which other directions can be experienced in ordinal values of breadth (to the right and left) or of height (up and down).

The third, the sense of externalization—that the object as perceived is always "out there" in front of the observer—probably has its counterpart in the subjective location of objects on the basis of touch or kinesthesis. While the apparent distance in this externalization may be uncertain, that the object appears "out there" is a compelling sensory fact.

There is reason to believe that these three attributes are innate—that the subjective response depends upon anatomic and physiologic conditions that existed prior to and are independent of the past personal experience of the individual. This is in contrast to the empirical view that the responses are best explained in terms of learning, on the basis of the past experience of the individual, through a kind of purposeful action.

These three basic attributes of visual perception establish at once the framework for the awareness of a three-dimensional visual space but entail two further questions: how stable are the subjective directional values associated with retinal elements, and how can the sense of externalization be delimited or elaborated to give rise to a concept of a visual distance or of differences in visual distances? It can be said that these constitute the central and the most difficult of the problems in visual physiology.

World of Objects

The man on the street seldom has reason to question whether the world of objects he sees is indeed the real world. It is evident to him that objects are where he sees them, and on the basis of his experience he need not concern himself at all about their being otherwise.

The visual scientist, on the other hand, must make a clear distinction between the visual space (a world of immediate experience) and the objective world of objects about him. This distinction is based philosophically upon his awareness of the difference between his immediate subjective visual experience and his knowledge about physical space. He reasons that an object in physical space may be rotated or displaced without deformation, and he assumes that the usual rules of geometry hold for the location of objects. In a visual space, with its constantly changing scene, the geometry may be different, in that visual space is bounded and in that changes in apparent shape and apparent distance do occur. One finds it logical to describe the visual position of points according to a kind of polar coordinate system—that is, according to angular separation and according to radial distances from a reference point, which is inferred to be the center of the subjective body image.

Many simple experiments demonstrate that a particular visual localization can lead to ambiguous or even incorrect interpretations of the positions and extensions of objects in space. Only a few need be mentioned here: certain geometrical illusions; physiologic diplopia in binocular vision; the moon illusion; the consistent error in the bisection of lengths; figural aftereffects; and the false spatial localization when differences in the magnifications of the images in the two eyes are introduced by lenses. Many of the discrepancies are small, however; the uninitiated usually are not aware of them unless their attention is called to them specifically. It is sufficient that some stable correlation exists between the visual interpretation of space and the actual location of objects in objective space. Philosophically even this objective world cannot be considered in an absolute sense, for certainly the objective world in which the earthworm exists is a different one from that of man.

Strongly entrenched in the literature of visual space perception is the empiristic point of view, which implies that the visual awareness of distance and of size can arise in no other way than by psychologic association and identification of the pattern of the retinal image with familiar objects and configurations of familiar objects, as known through the past experience of the observer (*1*). This is to say, the perception of depth arises from empirical factors or (as they are called) empirical cues. These include not only cues inherent in the image pattern itself but also those influences that are brought to bear on the perception by the motivation of the observer and by the particular significances he attaches to the stimulus patterns. This view implies a process whereby a selection or integration, or both, of cues from the image of the immediate scene occurs on the basis of prior experience—an experience that perhaps is gained partly through other sense modalities.

But according to a second point of view, only in occasional situations or in particular kinds of situations is it necessary to call upon past experience to evoke the sense of depth (*2*). The stimulus cues are considered a part of the stimulus-response processes of vision, and it is believed they can be so identified. To avoid the possible implication that these cues are necessarily empirical in nature, they are now usually referred to as secondary cues, as distinguished from the stimulus of disparity in binocular stereoscopic vision.

It is possible that the two points of view merge, for recent anatomic and physiologic studies suggest that in the diffuse reticular core of the central nervous system there may be mechanisms which can refine and organize the primitive qualities of sensations into what we call perceptions. These mechanisms may also provide the basis for mnemonic processes, may set the adaptation level for the reception of stimuli, and may initiate phenomena in the absence of peripheral stimuli (*3*).

In the perception of distance one must distinguish clearly between the impression of *relative* depth distances and what often is called *absolute* (or egocentric) perception of distance. The first refers only to the discrimination of differences in the distances to objects. It is possible and even probable that under many circumstances this relative sense of depth is only ordinal, enabling one to say, "This object is nearer, that is farther," but not to say how much nearer or farther (*4*). This is to say, relative depth perception is not the perception of differences in absolute distances.

It seems that nearly all of the well-known cues to spatial localization, at least by themselves, give rise only to relative depth localization. More than that, one might venture to add that any given cue taken alone can yield only an order-of-rank sense of depth. An example is the cue of interposition, or overlay, which is considered a powerful cue to depth perception. Usually the effect is demonstrated in drawings of overlapping figures; the partially occluded figure always is said to be farther than the overlapping figure, but one cannot ask what the difference in distances is. Hence, this cue is quantitatively useful only in the presence of other cues.

In judging distances there must always be a comparison object, so that the distance or the size of one object is compared to that of another, either temporally or spatially or even from memory (*4*). It is possible that in ordinary circumstances visual distances are only vaguely perceived. Not until the observer needs to do something which necessitates his discriminating actual distance is there called into play an appreciation of many factors and the action of feedback mechanisms associated with body movements which can lead to a conception of distance and of size that is sufficiently accurate for his immediate purposes.

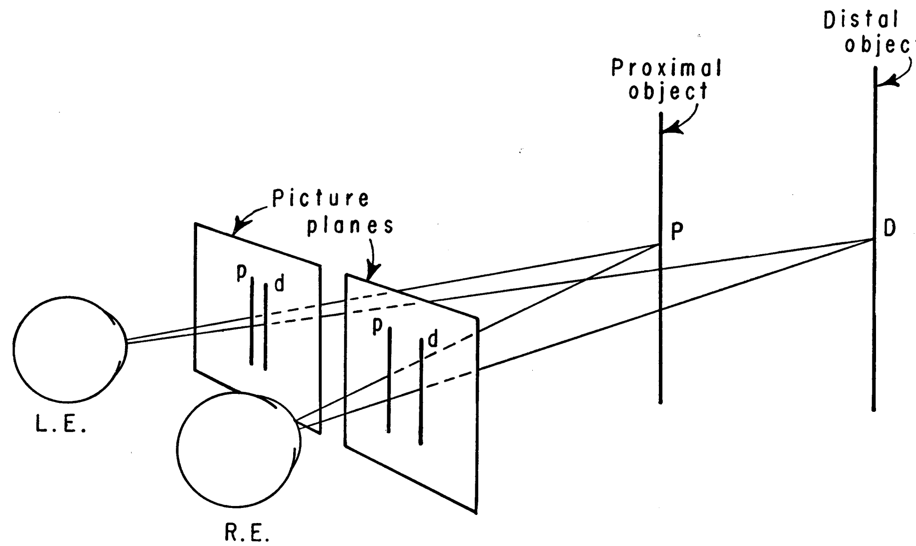


Fig. 1. Scheme of an experiment for testing stereoscopic depth perception in the absence of secondary cues to spatial localization.

Depth Perception

The visual perception of depth when the two eyes are used together constitutes a special problem in the study of visual space perception in general. It is true that as we glance about a room binocularly, then suddenly cover one eye, the spatial characteristics of the room appear to change little if at all. However, when critical depth perception is required, the striking superiority of using the two eyes simultaneously becomes evident immediately. One needs only to look through a window at the foliage of a number of trees at different distances to appreciate how readily one can discriminate the depth relationships with binocular vision, whereas with monocular vision the tree shapes tend to appear as an undifferentiated mass of leaves. Although some secondary cues to depth localization of objects are binocular in nature (such as aspect view), the principal and significant sense of depth arises through the phenomenon of stereopsis. The stimulus for stereopsis arises from the fact that each eye views objects in space from a slightly different spatial point. If the object distance is less than, perhaps, 200 meters, the differences between the patterns of the images in the two eyes are detectable—differences which the binocular processes can appreciate and respond to as differences in depth.

In the laboratory, stereoscopic depth perception usually is studied in experimental situations in which all secondary cues to depth perception are excluded. In Fig. 1, the eyes (*L.E.* and *R.E.*) are shown as though observing two thin plumb lines, *P* (proximal) and *D* (distal). Individuals with normal binocular vision see immediately that the plumb line *D* is farther away than *P*. The intersection of the light rays from these two lines with normal planes before the eyes results in pairs of vertical lines, *p* and *d*, for each eye. A vivid sense of difference in distance emerges from these paired stimulus patterns, either of which alone could give no hint of the spatial separation in depth of the lines *P* and *D*.

One notes that the separation of the lines *p* and *d* on the right-hand target is greater than that on the left-hand target. It is this difference in horizontal separation of the images, called a geometrical transverse disparity, that constitutes the necessary and sufficient stimulus for the emergence of stereoscopic depth perception. If the separation of the line images were less for the right eye than for the left, then in binocular vision the line *D* would appear the nearer. Pictures identical to these patterns can be presented to the eyes in a stereoscope, and the same visual experience of depth results.

Obviously there must always be at least two objects in the field of view before there can be a retinal disparity. Furthermore, a geometrical disparity will exist between the images of any two objects in a field of many objects, irrespective of the fixation point of the eyes.

The vividness of stereoscopic depth perception greatly exceeds the vividness of depth perception through secondary cues. One seems to sense the air space between the two objects. Indeed, from binocular space perception there arises an entirely new sensation that is not in the least suggested by observation with a single eye.

In recent years considerable research has been directed toward clarifying the fundamental notions about stereopsis (*5*). There are workers who insist that the disparity stimulus for the stereoscopic depth experience is also, and only, a cue to depth perception and that, as such, it should be placed in the list of other secondary cues to depth perception. In the main, the subjective response to these cues is considered to be empirical—that is, dependent upon the past experience of the observer.

There is evidence, however, that stereopsis may be a true stimulus-response physiologic process. Although acting concomitantly with other visual functions, it does not seem to be dependent upon them (*6*). The stimulus of disparity gives rise to a specific sensory response that is experienced as a depth difference. This is to say that the response depends upon anatomic and physiologic conditions that are independent of the prior experience of the individual. Ophthalmological experience in the surgical treatment of strabismus seems to bear out this idea that stereopsis either exists as an independent sensory response or does not exist.

Although the "depth" may be a specific sensory phenomenon related directly to the disparity between the images in the two eyes, it is possible if not probable that one learns early in life to associate "far" and "near" depths with the basic sensation that arises from the disparity between the images. In the same sense, one associates the word *red* or the words *shades of red* with light stimuli of certain wavelengths or combinations of wavelengths.

The magnitude of the relative depth perceived would be related similarly to the magnitude of the disparity. The association of scales of distance (in millimeters or meters, for example) with a stereoscopic response would have to be a learned association, but in no way does this consideration detract from the hypothesis that stereoscopic depth perception is a unique sensory response to disparities between the images in the two eyes of distally separated objects in space.

It is possible, however, that even in stereopsis the sensory response is basically ordinal. If so, it certainly is subjectively quantified, in that the image disparities for objects seen at points for which the depth differences are multiples of a given depth difference are related accurately to the actual depths in the way that geometry would predict. In conflicting situations this depth perception, being the result of a unique stimulus-response mechanism, would be less susceptible to the influence of the possible meanings attached to specific objects or to spatial configurations of the objects than would be depth perception from secondary cues. Stereoscopic depth perception, therefore, might be more easily suppressed than the latter, or overpowered by strong conflicting but more meaningful secondary cues to depth perception. Except when stereopsis is inhibited by the influence of conflicting secondary cues to depth perception, there is a strict correlation between the direction of the disparity and the perception of "nearer" or " farther" stereoscopic depth.

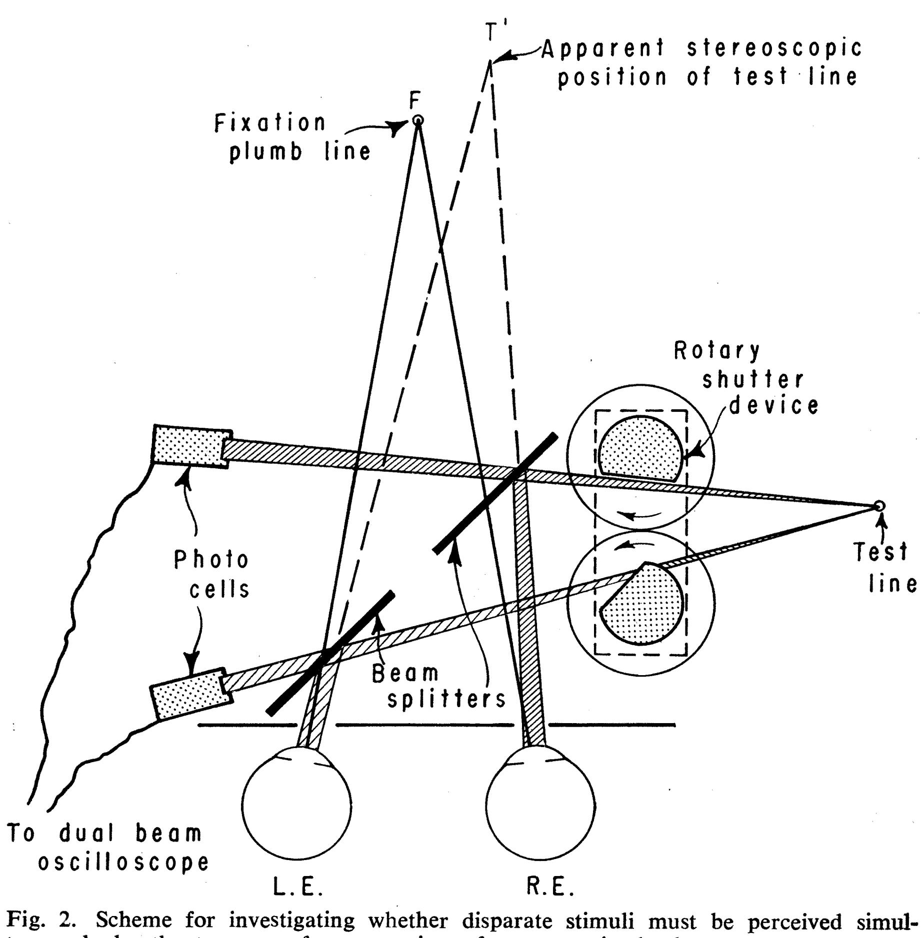


Fig. 2. Scheme for investigating whether disparate stimuli must be perceived simultaneously by the two eyes for perception of stereoscopic depth.

If the disparities between the images in the two eyes are made too large, however—as so often happens in the stereoscope—the character of stereoscopic depth changes and the perception may not even emerge at all; the image is seen "double," and the two half images appear indefinitely localized (*7*). Consequently it is possible to map out a spatial region about a given fixation point within which stereoscopic depth can be perceived and outside of which it cannot be. This statement can be verified crudely in the following manner.

Hold slender long needles vertically, one in each hand, with one above the other so that the two points almost touch. They should be seen against a uniform unstructured background. While looking directly at the upper needle, move the lower needle horizontally, nearer or farther away. You will notice that the lower needle, even with only a relatively small displacement, appears double. With slightly larger displacements the two half images are seen indefinitely localized; each appears at approximately the same distance as the needle fixated. Care must be taken to prevent head and eye movements. Large test objects should not be used, for then the difference in angular size would provide a cue as to difference in distance.

The limiting spatial region in which true stereoscopic vision occurs can be accounted for by the extent of overlapping in the arborization of neurons from corresponding retinal elements in their terminal areas of the cortex, or by the extent to which these innervations are diffused to neighboring nerve networks in these areas.

Stereoscopic depth perception under experimental circumstances is reported to have been achieved in those peripheral areas of the two retinas in which binocular vision is always an impossibility because of the obstruction of the field of view by the nose (*8*).

There is evidence that the disparate

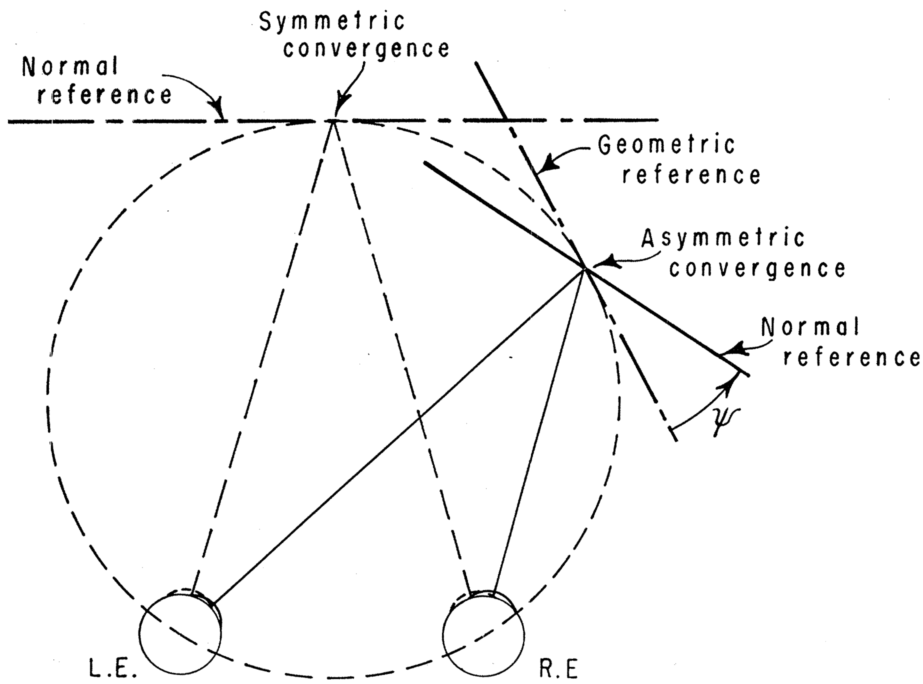


Fig. 3. Geometry indicating a change in the normal frame of reference when the subject's eyes turn to a position of asymmetric convergence.

images must be presented simultaneously to the eyes for stereoscopic depth to be perceived, but some reported findings are in conflict with this statement. A falling bead (in an experiment based upon the Hering test) was judged to be seen nearer or farther than a constant point of fixation of the two eyes (*9*). Then screens were arranged so that the upper part of the path of fall could be seen by one eye only and the lower part of the path of fall could be seen by the other eye only. The screens could be adjusted so that a central portion of the path of fall could be seen by both eyes. The stereoscopic thresholds (in angular disparity) and the mean disparity were obtained when the path of the falling bead was judged to be at the same distance as the fixation point. As the portion of the path of fall visible to both eyes was decreased until no part of the fall could be seen by both eyes simultaneously, stereoscopic sensitivity dropped tremendously and the stereoscopic judgment of depth became invalid. These results were taken as evidence that, for patent and valid perception of stereoscopic depth, the disparate images must be seen at the same time. Also, the results could indicate that the disparate images must be seen in horizontal juxtaposition for the perception of depth.

In a more recent experiment a scheme (shown in Fig. 2) is utilized in which, by reflection from two semitransparent mirrors (beam splitters), the eyes see a test line in stereoscopic depth relative to a fixated reference plumb line. The disparity between the images in the two eyes, and therefore the stereoscopic depth between this fixation line and the test line, can be changed and measured by slight contrary rotations of the beam splitters about vertical axes. A shutter of rotary type, operated electrically, exposes the test line to one eye and then to the other. The time lapse between exposures is changed by adjusting the angle (the phase) between the flat areas of the shutter cylinders. The actual exposures and the intervals between exposures were monitored by suitable photocells and a dual-beam oscilloscope. The disparity thresholds and standard error of presentations of the test line were determined when the stereoscopic image was judged to be at the same distance as the fixation line (or another reference line) for different delayed times of exposure.

The results indicated that so long as there was some overlap in the exposures, during which times the images of the test line were seen simultaneously, the stereoscopic depth threshold and the mean disparity when test and reference lines appeared to be at the same distance remained normal. As soon as the overlap had been eliminated, no stereoscopic depth perception could be really demonstrated — or, if stereopsis was seemingly present, it was invalid and uncertain. Increasing the luminance of the test line by 3 log units, so that there was possibly a longer persistence of the retinal images, produced little definite evidence of true stereopsis. The apparent need for simultaneity in the excitation of the two eyes to bring about a stereoscopic response implies that the stimulus gives rise directly to the response without the involvement of an intermediate higher central process. Or, on the other hand, it may imply that simultaneous integration of the disparate ocular images at an intermediate level is necessary for the unique depth response.

There are also statements in the literature to the effect that one can perceive stereoscopic depth from transversely disparate afterimages which are induced in each of the two eyes separately. In our laboratory this has not been conclusively verified, although experiments with electronic flash tubes are being continued. There is a suspicion that the controls have not been adequate in experiments previously reported. Stereoscopic depth can be perceived, of course, from disparate afterimages induced in the two eyes simultaneously.

The consistent emergence of stereoscopic depth perception from disparate images indicates a stable relationship via the cortex between definite retinal receptor elements in the two eyes (the stability of corresponding points). There is also some clinical evidence that this relationship tends to remain stable, except perhaps in children.

The stereoscopic perception of relative depth in a series of objects extending laterally in the visual field on either side of the fixation point is always referred to a particular over-all frame of reference that is concerned with veridical egocentric depth perception. When the eyes are symmetrically converged (Fig. 3), object points on either side of the fixation point are perceived stereoscopically to be farther or nearer relative to a surface that is (normally) at right angles to the egocentric direction of the fixation point. Points on this surface have images in the two eyes that conform to a certain pattern of horizontal geometric disparities. When the eyes turn to a position of asymmetric convergence, the same pattern of geometric disparities would correspond to points in space lying on a line designated in Fig. 3 as the geometric reference. A series of object points on this line would not appear normal to the egocentric direction of the fixation point. A rotation of the frame of reference occurs, corresponding to an over-all change in the pattern of disparities to conform to a normal reference (*10*). Objects are then judged nearer or farther than the point of fixation from this new frame of reference. The stimulus for the psychic change in the reference surface is thought to be the vertical (height) disparity between the two retinal images of the object fixated in asymmetric convergence; a geometric vertical disparity exists because the object fixated is at different distances from the two eyes (*10*). The geometric transverse disparities between the images in the eyes are re-interpreted in terms of this changed frame of reference. This frame of reference must be functional, and it exists because of the need for a stable egocentric spatial localization. Thus, the stereoscopic depth perception of "nearer" or "farther," when related to the fixation point in an egocentric estimation of distance, is reinterpreted in terms of a new frame of reference that may be in part empirical —that is, learned.

Secondary Cues and Stereopsis

In one's usual visual spatial localization of objects in familiar surroundings, the secondary cues play a dominant role. Any one of these secondary cues, in the absence of other types of supporting cues, may lead to ambiguous or at least inconsistent perceptions. In the totality of spatial localization, stereopsis as a single factor acts physiologically and more or less immediately in response to the stimulus of disparity; it therefore is not much concerned with meaning. In ordinary normal surroundings, the perception from secondary cues and the stereoscopic perception rarely conflict, and in binocular observation the spatial orientations of objects in space are more clearly correlated with the actual positions of those objects than under artificial conditions (*11*).

It is mostly in artificial situations, where the secondary cues to spatial interpretation may conflict with the stereoscopic localization, that the latter is overcome or suppressed. While the stereoscopic depth perception emerges automatically, with little regard to meaning or interpretation, many of the secondary psychologic factors are interpretative, since they are influenced by previous meaningful experiences. Thus it is that the human face, when viewed binocularly through a pseudoscope (which interchanges the right and left views), still appears convex, although from the disparities between the images one would expect it to appear concave.

These general facts regarding the roles of secondary and of stereoscopic factors in spatial orientation were brought out clearly in experiments in which a subject wore a meridional afocal magnifying lens before one eye for a long period (*12*). At first the subject wearing such a lens would report the typical distorted appearance of his surroundings attained through stereoscopic depth perception. If, for example, the lens was placed before the right eye to increase the magnification in the horizontal meridian, objects on the right side of the visual field appeared farther away and larger than those seen at the same relative distance on the left side. A desk top appeared tipped down on the right, up on the left; a wall in front of the subject appeared farther away at its right side, nearer at its left; the ground upon which the observer stood appeared slanted also, as though he stood on the side of a hill. His right hand appeared larger than the left, and the shapes of all objects appeared distorted. With the continued wearing of the lens, the observer became less and less aware of the spatial distortion. After 3 to 5 days the distortion was much less evident in familiar surroundings, where many secondary cues were present. After a week's experience, adaptation to the difference in magnification between the eyes, as introduced by the lens, seemed fairly complete.

Even then, however, when the same observer, still wearing the lens, found himself in fields or on a hill with high grass—that is, in surroundings where there were few secondary cues to localization—the distortion readily reappeared. This reappearance of the distortion occurred time after time, regardless of how long the lens had been worn. These observations indicate that one is able to adapt to a false stereoscopic localization in the sense that objects are seen in their known shapes, sizes, and positions. The adaptation persisted as long as the surroundings contained secondary cues in sufficient number—and perhaps of great enough significance—to dominate the spatial perception from stereopsis alone. Hence, although a subjective spatial adaptation occurred, the difference in magnification of the images was not compensated for physiologically or anatomically.

The phenomenon of adaptation for a distorted spatial perception is well known to ophthalmologists. Many patients, when they are given spectacles for the first time or when changes are made in their refractive correction, report an annoying distortion of visual space; but these patients usually (though not always) "get accustomed" to the new spectacles in a week or 10 days. The nature of this adaptation is by no means clear. There is no evidence that a loss of stereoscopic depth discrimination has occurred, even after a distortion of space is no longer apparent in familiar surroundings. Thus, the disappearance of the distortion with prolonged wearing of an afocal meridional magnification lens is not a complete suppression of stereoscopic vision, at least in the central portions of the binocular field. Perhaps one should look here for some psychologic change in the frame of reference of binocular stereoscopic space, similar to that which seems to occur in asymmetric convergence.

But also, these adaptations to the false spatial localization may be similar in nature to the adaptation of body-eye coordination (*13*) in experiments in which ophthalmic prisms are used with bases in the same direction before the two eyes. Fully half of the subjects completely compensated for the altered direction of visual space in about 4 days. The results indicate that these compensations occur only when body or hand movements are made by the subject and seen by the subject.

In certain surroundings (especially in the laboratory) where configurations of objects can be arranged to create a strong spatial illusion through inherent ambiguous or misleading secondary cues, it is found that under conditions of binocular observation the stereoscopic localization of details—even those dissociated from the illusory configuration — may be considerably falsified (*14*). However, stereoscopic depth perception is not necessarily suppressed in the presence of conflicting secondary cues, and in many situations it actually dominates the total spatial localization. Much depends on the complexity of the secondary cues and the extent to which they themselves may be ambiguous or contradictory. Great individual differences between subjects also may be found in this respect.

There is evidence that the psychologic mental set or expectancy affects the perception of depth. In critical tests of stereopsis, especially in those involving short exposure, strict attention and anticipation on the part of the subject are sometimes necessary. Also, in binocular observation of a number of objects in the field of view, eye movements seem to facilitate the perception of stereoscopic depth. Under artificial conditions of observation, stereoscopic depth sometimes fails to develop or develops only slowly, especially when the disparities between the images are large, as is often the case with drawings or, for example, x-ray films to be viewed in the stereoscope. Observers differ widely in this regard, and probably much depends on the extent to which the individual is accustomed to rely on the secondary factors. Stereoscopic depth sometimes fades with continuous staring at the pattern; this, however, occurs with other visual phenomena.

Accommodation and Convergence

One of the oldest theories of visual space perception, and certainly a most persistent one, is that accommodation and convergence provide stimuli for the egocentric spatial localization of objects fixated. This theory implies that there is a subjective sense of eye position derived from the activity of ocular muscles. Accordingly, the distance of an object would be sensed by the degree of accommodation (tensions in the ciliary muscles) required to keep the image clear on the retina, or by the amount of convergence (relative tensions in the extraocular muscles) required to fixate an object binocularly. Relative depth would be sensed by changes in the accommodation or changes in the convergence. By means of a triangulation procedure from the angle of convergence through a muscle sense, the individual would arrive at a concept of visual distance. The theory presupposes a reflex association between the tensions or changes of tension in the external recti muscles and in the ciliary muscles. So dominant was this theory at one time that proprioceptive cues were considered more important than all others for spatial localization, and the perception of distance was considered a direct response to proprioception.

The possible function of a proprioceptive sense in space perception is not entirely clear. Many carefully controlled experiments, in which secondary cues to spatial localization could be excluded, have shown generally that accommodation and convergence have no effect, or at most a negligible one, in spatial localization. Changes in accommodation and the concomitant changes in convergence have proved to be most unreliable guides to depth perception. It is concluded generally that spatial localization from convergence and accommodation, when these functions are completely isolated from the influence of secondary cues, proves to be impossible or is certainly very crude. This conclusion is maintained despite the rather recent discovery of muscle spindles (proprioceptive organs) in the extrinsic ocular muscles in human beings. It has been suggested that these muscle spindles may serve functions other than true proprioception, such as providing feedback innervations that would be useful in the refinement of eye movements for accurate fixation. Certainly it is difficult to understand how myosensory effects could account for the keenness of stereoscopic depth perception, which may have an angular disparity threshold as low as 12 seconds of arc.

Despite the experimental evidence, a few ophthalmologists and neurologists insist, on the basis of the general muscle physiology, that there must be some type of myosensory influence of convergence. Indeed, several experiments give results that are difficult to explain except in terms of such an influence. Identical targets viewed in a haploscope (a versatile type of stereoscope permitting accurate control of the accommodation and convergence of the eyes) appear nearer and smaller as the arms supporting the targets are converged to force an increased convergence of the eyes. Such a result seems to rest upon at least some myosensory influence related to eye movements—or, if not, it seems to be related to an "innervation sense" or at least to a sensory cue from pre-innervational intent for eye movements under the changed tensions of the ocular muscles. On the other hand, if, during the observation of a near object, prisms are introduced before the eyes (with bases placed toward the nose) so that the visual axes are forced to positions of less convergence, as though a more distant object were being fixated, the subjects generally report that the object actually appears nearer and enlarged, not farther away. This apparent change in distance is probably due to the optical distortion inherent in the prisms; so, if a myosensory cue does exist here, it is indeed subservient to or inhibited by other cues.

Chevasse is said to have insisted that there must be an ocular sense of myosensory position, but he made the further assumption that the influence from this sense is suppressed unless the sense is reinforced by the presence of other cues to spatial localization. If this assumption is true, then it will be virtually impossible to study experimentally the sensory function of ocular proprioception.

The physiologic role played by eye movements, both voluntary and involuntary, in stereoscopic depth perception needs to be clarified further. Eye movements do seem to enhance the subjective sense of depth, but their true influence is difficult to demonstrate under controlled experimental conditions.

A Geometry for Visual Space

Because subjective visual space comprises a limited area filled with objects having distances and sizes, it is natural to assume that somehow it may be metrically related to, or can be mapped in terms of, objective space. In recent years there has been considerable interest in a theory based upon the hypothesis that perceptual space in binocular vision is a priori three-dimensional. According to this, a sense of distance based upon convergence of the eyes is a basic quality of binocular visual space, and in the absence of the possible influence of secondary cues its structure is uniquely determined. A mathematical model was postulated by Luneburg (*15*) to describe the structure of binocular visual space as related metrically to objective space. The accounts of this work and accounts by some of Luneburg's followers are not easily understood except perhaps by readers who are quite sophisticated mathematically. A great deal of the original mathematical formulation by Luneburg has been modified subsequently in the light of new experiments (*16*) that have been conducted since his untimely and unfortunate death.

Within limits, "the psychometric coordination of numbers to sensations is uniquely determined if the sensations allow recognition of greater or smaller, and of greater or smaller contrast" (*15*). The use of numbers in the speci-

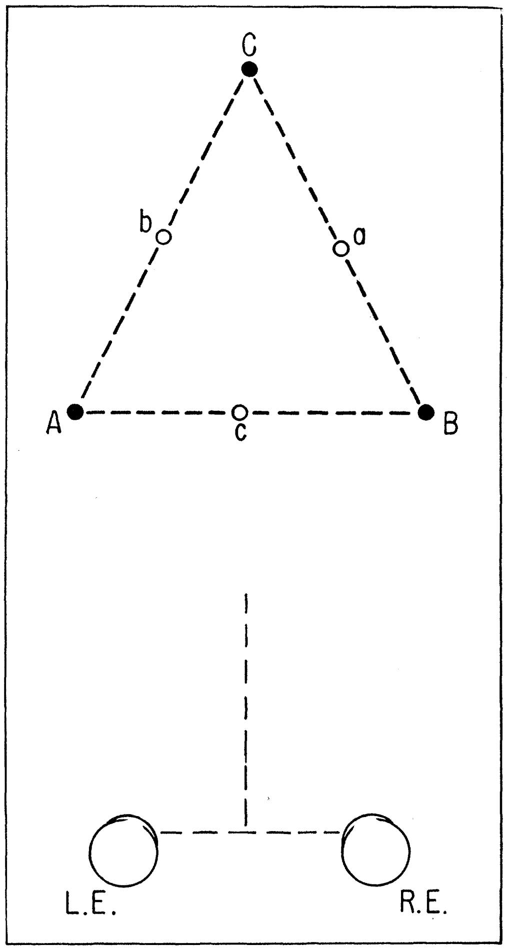
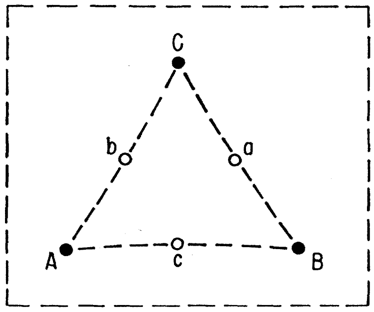


Fig. 4. A simple experiment used by Blank (*17*) to test for the sign of the curvature of binocular visual space.



fication of subjective visual space is based upon certain axioms that depend on commonly experienced and qualitative aspects of space perception (*16*). There remains an arbitrary factor in the description, however, which means that only comparative distances are specified, and a subjective distance cannot be directly equated to an objective distance.

One experimental approach to the problem is to arrange a series of object points in space so that they conform to a certain subjective criterion and then measure their actual positions. For example, suppose that an observer adjusts a number of points in the visual plane so that they appear to lie on a series of imagined lines that are equidistant from each other and perpendicular to the subjective direction from the observer's body image to a distant reference point. Such a series would constitute one element of a subjective coordinate system in arbitrary subjective and unspecifiable metric units. Similarly, a number of points could be adjusted so that they would appear to lie on a series of imagined equidistant lines parallel to the same subjective direction from the body image to a distant point (the so-called alley experiments). Theoretically these two types of subjective criteria together would constitute a rectilinear coordinate system of subjective visual space. Then one should need only to study the actual objective positions of the various points so adjusted in order to arrive at some idea of how one kind of space might be mapped from the other.

Certain important complications occur because of the meanings attached to the words *parallel* and *equidistant* in the instructions. Even so, such experiments and the subsequent mathematical analysis have afforded evidence that the structure of binocular visual space might well be non-Euclidean — and more particularly, of the hyperbolic type. Whether a geometry is Euclidean or non-Euclidean is decided on the basis of the behavior of parallels. The actual settings of the object points in the alley experiments differed according to the instructions "equidistant" or "parallel." The ordinary observer has great difficulty in making these alley settings partly because of the physiologic diplopia that occurs and partly because of difficulties in the interpretation of instructions. Hence, the precision of the settings left much to be desired, and there were considerable differences between subjects. Consequently, the results reported have not been considered conclusive.

More recently, Blank (*17*) has reduced the number of basic axioms for the theory and has shown that specifying an egocentric distance is unnecessary and that the character of the metric for binocular subjective space can be obtained merely from consideration of relative distances based upon disparities of the images in the two eyes. He has used the proposition that any particular geometry is independent of the coordinate system used and of the origin of that system. Thus, in principle, one ought to be able to determine the curvature of binocular visual space without "employing knowledge of the particular relationship between the physical stimulus and the associated visual geometry." He set up a simple experiment (Fig. 4) in which the subject views three point light sources (A, B, and C) arranged in the form of an isosceles triangle at eye level in a horizontal plane. Other point light sources (a, b, and c) were adjusted, one at a time, by the subject until one appeared to lie at the mid-point of each side of the triangle. The results for most subjects, applied generally, indicated sides that curved inward (Fig. 4, inset boxed by dashed lines). This finding was taken as evidence that subjective visual space is hyperbolic (negative-curvature) non-Euclidean.

The question must be raised, however, whether the structure of subjective visual space really exists except by virtue of seeing particular actual objects in objective space. Without these objects, visual space is indefinite. The structure of visual space then might well depend entirely upon the relative depths sensed as part of the perceptions obtained from particular cues of separate, specific objects in space. Such visual space could easily be inconstant and could even be affected by ambiguous and conflicting influences. This is more likely to be true in monocular than in binocular vision. In regard to this point, it is difficult for the ordinary student of visual physiology to recognize that the structure of visual space obtained through binocular vision is something apart from the structure which would be obtained through monocular vision.

Conclusion

At the conclusion of this discussion it is important to keep in mind the influences of all the complex processes involved in visual spatial localization, among which stereopsis is only one. The various factors and cues for this spatial localization interact with, complement, reinforce, and perhaps even inhibit one another, depending upon the varying visual surroundings of the moment and upon the physiologic perfection of the visual apparatus. In one's daily work probably no single factor or group of factors dominates at all times. "Any one who knows how pliable our spatial visual perceptions are under the influence of various conditions of observation and under the influence of past experience, taken into account consciously or unconsciously, should not be surprised at the multiplicity of results of observations on different objects and with different observers" (see *18*).

It is not surprising, therefore, that if one selects any single visual factor and attempts to find its specific importance in a subject's ability to perform a given complex task, often no correlation or only a poor correlation is found. In particular, one can refer to the poor correlation that obtains between stereoscopic acuity, as measured on a particular test apparatus in the laboratory, and the flying ability of the aviator. This low correlation and the equivocal associations reported in the literature have been construed by some to mean that stereopsis is of little value to the pilot, but the conclusion seems unwarranted and unfortunate.

In this article I have presented (with a degree of oversimplification) some of the basic and yet up-to-date concepts regarding visual perception of space. A number of perplexing problems have been pointed out, with methods of approach to several of them. In such a discussion it is difficult to avoid becoming enmeshed in the psychology and philosophy—and above all, the semantics—of the general field of perception. Even so, I feel that it is best to adhere to those concepts that allow one to approach the problems of visual perception in a manner providing, as nearly as possible, a physiologic basis for understanding them.

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Rockets, Resonance, and Physical Chemistry

The problems encountered with solid-fuel rockets bring together an amazing variety of disciplines.

F. T. McClure

From time to time one hears much discussion of the importance of interdisciplinary endeavors. In recent years, in particular, numerous attempts have been made to encourage and inspire such efforts. This concern clearly arises from the fact that as science continually broadens its base and vastly increases the sum of our knowledge, there is a concurrent tendency toward increasingly narrow specialization. While on the whole such specialization has been good and, in fact, essential to progress on the many individual fronts of science, it is nevertheless true that many of the problems which face us do not fall neatly into the defined specialized categories. Thus, there is great need to bridge the gap between the specialties in order that all pertinent information may be used in formulating a solution of the problem at hand. The breathtaking rapidity of scientific and technological advances in these days, and their impact on our whole society, has apparently created a more widespread awareness of this question. It is in this context that the modern pleas are to be understood.

Sometimes, however, there appears to be a tendency to regard this problem as something qualitatively new in man's experience, and so requiring a new kind of man. I think that this is a mistake. Scientific history is filled with examples of the outstanding contributions of men who have cut across formalistic and pedantic lines—men who have brought fresh viewpoints from one field into another and have solved vital problems which did not appear to merit the attention of experts in any one of the then accepted disciplines. Further, I venture to suggest that it is the generalists who have provided opportunities for specialists to find fruitful areas, and not the converse. I would be surprised if this view were not considered so obvious as to be trite, particularly among chemists aware of the history of their profession.

I could easily forgive a reader if he were now inclined to ask what this bit of philosophy has to do with my topic. Merely this: the science of solid-fuel engines provides a modern simple example—and there are many more so-

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