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THE INTERNATIONAL SCIENTIFIC SERIES.

SIGHT:

AN EXPOSITION OF THE PRINCIPLES OF *MONOCULAR AND BINOCULAR VISION.*

BY

JOSEPH LE CONTE, LL. D.,

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GEOLOGY AND NATURAL HISTORY IN THE UNIVERSITY OF CALIFORNIA.

WITH NUMEROUS ILLUSTRATIONS.

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PREFACE.

In writing this treatise I have tried to make a book that would be intelligible and interesting to the thoughtful general reader, and at the same time profitable to even the most advanced specialist in this department. I find justification for the attempt in the fact that there is not, to my knowledge, any work covering the same ground in the English language. Vision has been treated either as a branch of optics or else as a branch of physiology of the nervous system. Helmholtz's great work on "Physiological Optics," of which there exist both a German and a French edition, is doubtless accessible to scientists, but this work is so technical that it is practically closed to all but the specialist. I believe, therefore, that the work which I now offer meets a real want, and fills a real gap in scientific literature.

The form in which the subject is here presented has been developed entirely independently, and as the result of a conscientious endeavor to make it clear to students under my instruction. As evidence of this, I would draw attention to the fact that, out of one hundred and thirty illustrations, only about twelve have been taken from other writers. On those points in which I differ, not only in form but in matter, from other writers, I am willing to abide the judgment of those best qualified to decide.

I have devoted a large, perhaps some may think a too large, space to the discussion of binocular vision. I have done so, partly because I have devoted special attention to this department, partly because it is so very imperfectly presented by other writers, but chiefly because it seemed to me by far the most fascinating portion of the whole subject of vision.

As a means of scientific culture, the study of vision seems to me almost exceptional. It makes use of, and thus connects together, the sciences of Physics, Physiology, and even Psychology. It makes the cultivation of the habit of observation and experiment possible to all; for the greatest variety of experiments may be made without expensive apparatus, or, indeed, apparatus of any kind. And, above all, it compels one to analyze the complex phenomena of Sense in his own person, and is thus a truly admirable preparation for the more difficult task of analysis of those still higher and more complex phenomena which are embraced in the science of Psychology.

BERKELEY, CALIFORNIA, *May 20, 1880.*

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SIGHT.

INTRODUCTORY.

THE RELATION OF GENERAL SENSIBILITY TO SPECIAL SENSE.

Sensory nerve-fibers are cylindrical threads of microscopic fineness, terminating outwardly in the sensitive surfaces and sense-organs, and inwardly in the nerve-centers, especially the *brain.* Impressions on their outer extremity are transmitted along the fiber with a velocity of about one hundred feet per second, and determine changes in the nerve-centers, which in turn may determine changes in consciousness, which we call sensation. The simplest and most general form of sensation is what is called general sensibility, or common sensation. This is a mere sense of contact, an indefinite response to external impression. It gives knowledge of externality—of the existence of the external world—but not of the properties of matter. The lowest animals possess this, and nothing more. But, as we go up the scale of animals, in order to give that wider and more accurate knowledge of the various properties of matter necessary for the complex relations of the higher animals, sensory nerve-fibers are differentiated into several kinds, so that each may give clear knowledge of different properties. Thus, for example, the first pair of cranial nerves—olfactive—is specially organized to take cognizance of certain impressions, called smells, and nothing else. If, therefore, these nerve-fibers are irritated in any way, even mechanically, by scratching or pinching, they do not *feel* but *perceive* an odor. The second pair of cranial nerves—the optic—is specially organized in a truly wonderful way to respond to the ethereal vibrations called light, and nothing else. If, therefore, these nerves be mechanically irritated, we do not *feel* anything, but *see* a flash of light. In a similar manner, the eighth pair—auditive nerve—is specially organized to respond to sound-vibrations, and nothing else; and therefore mechanical irritation of this nerve produces only the sensation of sound. Similarly, the ninth pair, or gustative nerve, is organized for the appreciation of taste only; and, therefore, a feeble electric current through this nerve produces a peculiar taste.

We have in these facts only an example of a very wide law, viz., the law of differentiation. In the lowest animals all the tissues and organs which are so widely distinct in the higher animals are represented by an unmodified *cellular structure*, performing all the functions of the animal body, but in an imperfect manner. Each cell in such an organism will feel like a nervous cell, contract like a muscular cell, respire like a lung-cell, or digest like a stomach-cell. As we go up the animal scale, this common structure is differentiated first into three main systems, viz., the *nutritive* or epithelial system, the *nerve*-system, and the *blood*-system: the first, presiding over absorption and elimination, i. e., exchange of *matter* between the exterior world and the organism; the second, over exchange of *force* between exterior and interior by impressions determining changes in consciousness, and by will determining changes in external phenomena; the third, presiding over exchanges between different parts of the organism. The first kind of exchange may be likened to foreign commerce; the second, to exchange of intelligence by telegraphic communication with foreign countries; the third, to the internal carrying trade. These three systems are very early differentiated in the embryo, since they are severally produced from the three primitive layers of the germinal disk, viz., the *endoderm*, the *ectoderm*, and the *mesoderm*.

Neglecting now all but the second or nervous system as we still go up, this is again differentiated into three sub-systems, viz., the *conscio-voluntary*, or *sensori-motor*, the *reflex*, and the *ganglionic*, each with its center and its afferent and efferent fibers. Neglecting, again, the two others, and selecting only the sensori-motor, the sensory fibers of this sub-system are again differentiated into five kinds, each to respond to a different kind of impression, and perceive a different property, viz., the five special sense-fibers for sight, hearing, smell, taste, and touch. Even these are probably again further differentiated; for the perception of different colors and different musical sounds is probably effected by means of special fibers of the optic and auditive nerves. The following diagram (Fig. 1) illustrates these successive differentiations.

Gradation among the Senses.—Now all these higher special senses may be regarded as the result of refinements of common sensation—each a more *refined touch*. Coarse vibrations are perceived by the nerves of common sensation as a *jarring*. When the vibrations are so rapid that there are sixteen complete movements back and forth in a second, an entirely different sensa-

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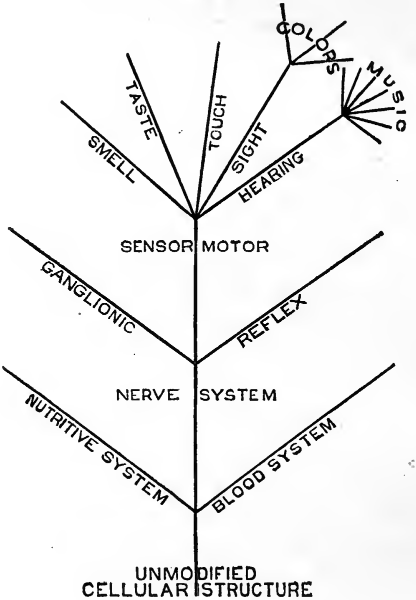
tion is produced, which we call *sound*. The vibrations are no longer perceived by the nerves of common sensation, but a special nerve—the auditive—is organized to respond to or co-vibrate with them. As the vibrations increase in number, they are perceived as higher and higher pitch, until they reach the number of about 40,000 in a second. This is the highest pitch the ear can perceive, the quickest vibrations the auditive nerve can respond to. Beyond this there is absolute silence, but only because we have no nerve organized to co-vibrate with these more rapid undulations. These vibrations, inaudible to us, may possibly be perceived by some lower animals, as, for example, insects; we can not

Fig. 1.



tell. After a long interval, vibrations again appear in consciousness as light. The vibrations which produce this sensation are so rapid—399,000,000,000,000 in a second—that they can be conveyed only by the ethereal medium. For the perception of these vibrations, a peculiar and wonderful organization is necessary, found only in the optic nerve. Above the number just given, ethereal vibrations are perceived as different colors, in the order seen in the spectrum, until 831,000,000,000,000 is reached. Beyond this we have no nerve capable of responding.

The gradation among the special senses may be shown in a different way. In *touch* we require direct and usually *solid* contact; in *taste*, *liquid* contact, for unless a body is soluble it can not be tasted; in *smell*, the contact is *gaseous*, for unless a body is volatile or vaporizable it can not be smelled. In this last case, the perception of objects at a distance begins; still it is by direct contact, for particles from the distant body must touch the olfactive nerve. In *hearing*, there is no contact of the sounding body, but the vibrations are conveyed through a medium. We perceive at a distance, limited only by the extent of the atmosphere and the energy of the initial vibration. In *sight*, finally, we perceive objects at a distance which is illimitable, the vibrations being conveyed by a medium which is universal, and too subtile to be recognized except as the bearer of light.

Again, commencing with *taste:* In this sense we distinctly perceive that the sensation is subjective—is in *us*, not in the body tasted. In *smell*, there is an equal commingling of subjectiveness and objectiveness. We distinctly *perceive* the sensation as in the nose, and yet by experience we have learned to refer it to an object at a distance. In *hearing*, we already refer the cause so completely to a distant object that there is but the smallest possible remnant of a consciousness of sensation in the ear; the sound does not seem to be in the ear, but in yonder bell. Finally, in sight, the impression is so completely projected outward, and the consciousness of anything taking place in the eye so completely lost, that it is only by careful analyses that we can be convinced of its essential subjectiveness.

The order which we have given above is also the order of increasing specialization and refinement of the senses. But only in the two higher senses—only in those senses in which there is no direct contact, but the impressing force is conveyed by means of vibration through a medium—only in these highest senses do we find that, besides the specialization of the nerve-fibers to respond to peculiar vibrations, also an elaborate *instrument* is placed in front of the specialized nerve in order to intensify the impression and give it more definiteness. It is wholly by virtue of this supplementary instrument that we are able to hear not only sound but *music*, or to see not only light but *objects*. The lowest animals in which an optic nerve is found perceive light, but not objects; because, though the *specialized nerve* is present, the appropriate instrument is wanting. It is on these two higher senses that fine art is wholly and science is mainly founded. The specialized nerve and the instrument for intensifying and making definite the impression are together called the *sense-organ*. It is of the most highly specialized of these nerves and the most refined of these instruments, the highest of the sense-organs, *the eye*, that we are now about to treat.

It may be well to bear in mind and keep distinct what may be called the direct *gifts* of sight, and what are added by the mind as *judgments* based upon these gifts. The direct data are only *light*, its *intensity*, *color*, and *direction.* These are incapable of further analysis, and are therefore simple sensations. *Outline form* may possibly be added, though this may be analyzed into a combination of directions. But *solid form*, *size*, and *distance*, though they may seem to be immediately perceived, are not direct perceptions, but only very simple judgments based on the data given above. We only state these facts now that they may be borne in mind. We hope to substantiate them hereafter.

PART I.

MONOCULAR VISION.

CHAPTER I.

GENERAL STRUCTURE OF THE HUMAN EYE, AND THE FORMATION OF IMAGES.

SECTION I.—GENERAL STRUCTURE OF THE EYE.

General Form and Setting.—The eye is nearly spherical in shape, and about an inch in diameter. The socket in which it is set is not a hollow sphere, but an irregular hollow cone or pyramid. Evidently, therefore, the deeper and smaller parts of the hollow must be filled with something else. It is filled with loose connective tissue, containing fat. On this, as on a soft cushion, the eyeball rolls with ease in every direction. The eye proper is really *behind the skin*, or outer integument of the face, for the skin which covers the lids turns over the edge (Fig. 2, *l l*) and passes under the lids, becoming here thin and tender mucous membrane; it is then reflected from the back part of the lid to the anterior surface of the white portion of the ball (Fig. 2, *a a*), then passes forward again over the ball as far as the clear part, or cornea (Fig. 2, *c c c*), and then entirely over this, although very closely attached. If carefully dissected off, it would leave the eyeball behind it. This mucous covering of the anterior portion of the eyeball is called the *conjunctiva.*

Illustrations.—In ordinary inflammations of the eye, it is this mucous membrane which is affected, and not the eye proper. Disease of the eye proper is a far more serious matter.

When motes get into the eye, they can not go beyond easy reach, viz., beyond the reflection of the mucous membrane, from the lid to the ball, at the points *a a.*

The Muscles.—We all know the rapidity and precision with which the eye turns in all directions. This is by means of six slender muscles. Four of these are called the *straight* muscles, and two the *oblique* muscles. The *straight* muscles all rise at the bottom of the conical socket, diverge as they pass forward, and grasp the eyeball above, below, on right and left side, just in front of the middle or equator of the globe (Fig. 3). They are called severally *superior*, *inferior*, *external*, and *internal rectus.* The first turns the ball upward, the second downward, the third to the right, and the fourth to the left, if we are speaking of the right eye. This is their action expressed *generally;* but, by reference to Fig. 20, on page 54, it is seen that the axis of

FIG. 2.

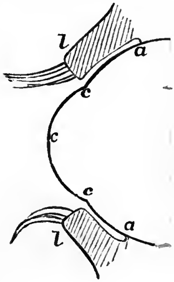
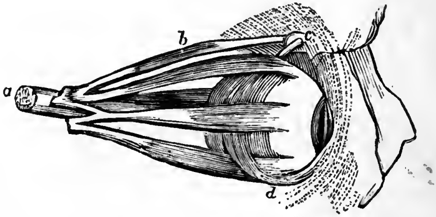


FIG. 3.



MUSCLES OF THE EYEBALL.—*a*, optic nerve; *b*, superior oblique muscle; *c*, pulley; *d*, inferior oblique. The other four are the recti.

the eye is not coincident with the axis of the socket, and, therefore, the action of the superior rectus by itself is not only to turn the eye upward, but also to rotate it a little on its axis inward toward the nose; while the inferior rectus not only turns the eye downward, but also rotates it a little on its axis outward.

The *oblique* muscles are *superior* and *inferior*. The *superior* oblique (Fig. 3, *b*) rises like the recti at the bottom of the socket, passes forward, contracts to a slender tendon, passes through a loop situated in the forward part of the socket, on the inner (nasal) and upper side (Fig. 3, *c*); it then turns upon itself backward and outward, passes over the globe obliquely across the equator, and is attached to the sclerotic, or white coat of the eye, on the outside, a little behind the equator. From its last direction it is evident that its function is to turn the eye outward and downward, and at the same time to rotate it on its axis inward, i. e., sinistrally for the right eye and dextrally for the left. The *inferior* oblique (Fig. 3, *d*) rises from the anterior, inner, and lower portion of the socket, passes outward and backward beneath the ball, and, crossing the equator obliquely, is attached to the ball on the outside, a little behind the equator. From its direction it is evident that its function is to turn the eye inward and upward, and at the same time to rotate it on its axis outward, i. e., dextrally—or like the hands of a watch—for the right and sinistrally for the left.

Illustrations of these Actions.—If we desire to look upward, we bring into action the two superior recti; if downward, the two inferior recti; if to the right, the exterior rectus of the right and the interior rectus of the left eye; if to the left, the external rectus of the left and internal of the right. If we desire to look at a very near object, as, for example, the root of the nose, then the two interior recti are brought into action. But we can not voluntarily bring into action the *two exterior recti* to turn the eyes outward, nor the *superior rectus* of one eye and the *inferior rectus* of the other, so as to turn the one eye upward and the other downward. The reason of this is because such motions, so far from subserving any useful purpose, would only confuse us with double images, as will be explained hereafter, and therefore have never been learned.

Malpositions of the eye, such as squinting, are the result of too great contraction of one of the recti muscles, usually the internal. It is often cured by cutting the muscle, and allowing it to attach itself to a new point.

The Eyeball.—We have thus far spoken only of what is external to the ball, viz., the socket, the muscles, etc. We come now to explain the structure of the ball itself. Suppose, then, the ball be removed from the socket, and the muscles and connective tissue be dissected away; let us examine more minutely its form and structure.

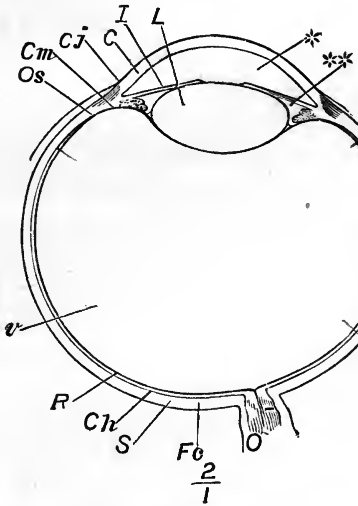
The eye thus separated is nearly a perfect globe, except that the front part is more protuberant (Fig. 4).

1. The outer investing coat, except the small protuberant front part, is a strong, thick, fibrous membrane of a porcelain-white color, called the *sclerotic*. This is partly exposed in the living eye, and is called the "white of the eye." By its strength, toughness, and elasticity it gives form without rigidity. On this account the ball yields to pressure, but quickly regains its form. It also serves as the basis of attachment for the muscles. If we compare the eye to a globular watch, then the sclerotic represents the outer case.

2. The more protuberant part of the ball is covered

with a thick, strong, but very *transparent* membrane, called the *cornea* (*C*, Fig. 4). It corresponds to the crystal of the watch. Its function is to admit the light, and at the same time to refract it, so as to assist in forming the image, as will be explained hereafter.

Fig. 4.



Section of the Eye.—*O*, optic nerve; *S*, sclerotic; *Ch*, choroid; *R*, retina; *v*, *vitreous* body; *Cm*, ciliary muscle; *Cj*, conjunctiva; *C*, cornea; *I*, iris; *L*, lens; *, aqueous humor; **, ciliary body or zonule of Zinn.

3. Running across from the circle of junction of the cornea with the sclerotic, and thus cutting off the more protuberant clear part from the main part of the ball, and thus corresponding in position to the face of the watch, there is an opaque, colored plate called the *iris*, *I*. It is the colored part of the eye, black, brown, blue, or gray, in different individuals. This transverse plate is not perfectly flat, but protrudes a little in the middle. In its center is a round hole, called the *pupil*,

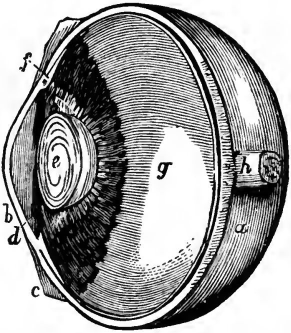
corresponding in position with the hole in the watch face for attachment of the hands. The pupil seems to be jet black, because the observer looks through the pupil into the dark interior of the ball. The function of the pupil is to admit, and at the same time regulate the amount of, light.

4. *Linings.*—Thus much is visible to the naked eye without dissection. But, if the ball be now carefully opened, the part behind the iris is found to be lined with two thin membranes. (*a.*) Immediately in contact with the sclerotic is the *choroid*, a thin membrane, the cells of which are colored with black pigment, which gives it a deep-brown, velvety appearance. Its function is to quench the light as soon as it has done its work of impressing the retina. The anterior portion of the choroid, separated from the sclerotic, drawn together as a curtain, and thickened by muscular tissue, forms the *iris* already described. Just before separating from the sclerotic to form the iris, it splits into two layers: one, the anterior, goes to form the iris, as already said, while the other, the posterior, is gathered into a circular, plaited curtain, or series of converging folds, which surrounds the outer margin of the lens (to be presently described) like a dark, plaited collar. These plaits, or folds, seventy to seventy-two in number, are called the ciliary processes (Fig. 5, and *e*, Fig. 19, p. 43). Beneath this dark, plaited collar, and therefore in contact with the sclerotic, is a muscular collar, with radiating fibers, called the ciliary muscle. (*b.*) Within the choroid, innermost and most important of all, is the *retina*. This is, in fact, a concave expansion of the optic nerve (*O*, Fig. 4). This nerve, coming from the brain, enters the eye-socket near its point, penetrates the sclerotic and the choroid, then spreads out within as a thin, concave

membrane of nerve-tissue, covering the whole interior of the ball as far forward as the ciliary collar. Its function is to receive and respond to the impressions of light. Its wonderful structure and functions will be explained hereafter.

5. *Contents.*—The ball thus described is not hollow and empty, but filled with refractive media, as transparent as finest glass. These are:

Fig. 5.



Section of Eye.—*a*, sclerotic; *b*, cornea; *c*, conjunctiva; *d*, iris; *e*, lens; *f*, ciliary muscle behind the dark ciliary processes; *g*, retina; *h*, optic nerve. (After Cleland.)

(*a.*) *Crystalline, or Lens.*—Immediately behind the iris, and in contact with it, is found the crystalline. It is a flattened ellipsoid, or double convex lens, as clear as finest glass, about one third of an inch in diameter, and one sixth of an inch in thickness, firm enough to handle easily, but elastic and easily yielding to pressure. On section it is found to consist of layers, increasing in density from surface to center, as shown in Fig. 5, *e*, and in Fig. 13, on page 37. The lens is invested with a very thin, transparent membrane, *capsule of the lens*, which not only invests it, but continues outward as a plaited curtain, to be attached to the sclerotic near the junction of the cornea. The elastic rigidity of the sclerotic pulls gently on this curtain and makes it taut, and the taut membrane in its turn presses gently on the elastic compressible crystalline and slightly *flattens* it. We shall see the importance of this when we come to speak of the adjustment of the eye for distance.

The perfect transparency of the lens is obviously necessary for distinct vision; cataract, a common cause of blindness, arises from its opacity.

The lens, with its continuing curtain, completely divides the interior of the ball into two compartments, an anterior and a posterior.

(*b*.) The anterior chamber is filled with a clear, aqueous liquor, called the *aqueous humor* (Figs. 4 and 5), a small portion of which is behind the iris, but by far the larger portion between the iris and the cornea. The two parts are in connection through the pupil. If the cornea be punctured, the aqueous humor runs out, the clear protuberant part of the eye collapses, and the sight is for the time ruined. If, however, the wound heals without scar, or if the scar be to one side of the direct line of sight, the cornea will fill again and the sight may be recovered.

(*c*.) The posterior and much larger chamber is filled with a transparent, glassy substance, about the consistence of soft jelly, called the *vitreous humor*. This humor is in direct contact with the lens and curtain in front, and with the retina over its whole globular surface.

Explain here about light—reflectn—refractn &c

SECTION II.—FORMATION OF THE IMAGE.

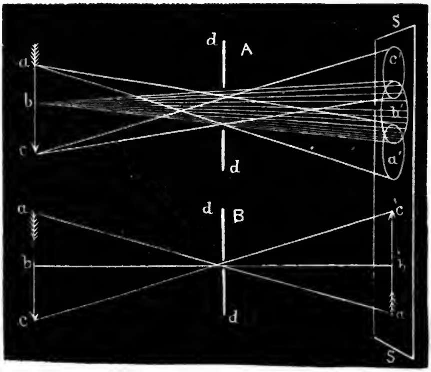
The eyeball, as thus described, may be regarded as consisting essentially of two distinct portions, viz.: 1. A nervous expansion, the retina, specialized for responding to light-vibrations; 2. An optical instrument, the lens apparatus, placed in front of the retina, and specially arranged to make the impression of light strong and definite, by *means of an image*. These two are entirely different in their origin. In embryonic development, the one is an *outgrowth* from the *brain*, the other an *ingrowth* from the epidermis and cutaneous tissues. These afterward meet and unite to form this wonderful organ.

Now the sole object of this complex instrument is the formation of a perfect *image on the retina.* Without images we would perceive light, but not objects; and distinctness of objects is exactly proportioned to distinctness of retinal images. If the image of an object is distinct, the object will be distinct; if the image is blurred, the object, both in outline and in details of surface, will be blurred. If there is no image, no object will be visible. Therefore the image *must be* a fac-simile of the *real* object, for the *apparent* object *will be* a fac-simile of the image.

Conditions of a Perfect Image.—A serviceable image must be sufficiently bright, and perfectly sharp and distinct in outline. Brightness only requires a sufficient amount of light. In order to be perfectly distinct, it is necessary that rays from different points in the object, even the most contiguous, should not mix on the image, but all the rays from each point on the object must be carried to its own point on the image. Now, it is impossible that both of these conditions should be fulfilled, except by some such arrangement as we find in the eye.

For see: suppose the light to enter by a hole only, like the pupil; and, further, in order that there be light enough, let the hole be somewhat large; then the light, diverging from any point, *b*, Fig. 6, *A*, of the object *a b c*, and entering the hole *h* of diaphragm *d d*, will form a diverging pencil, and spread out over the whole circle *b′*, on the screen *s s*. Similarly, the rays from *a* will spread out and form the circle a', and from c the circle c'. Thus it is seen that rays from *widely different* points in the object mix with each other on the receiving screen; much more, then, would rays from *contiguous* points of the object mix. In such a case, the mixing is so great that no recognizable image is formed at all.

Fig. 6.



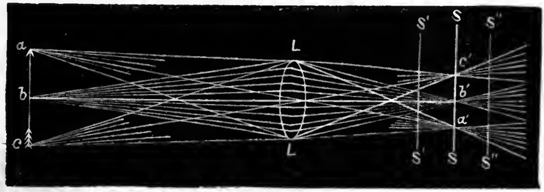
As the hole becomes smaller, the circles of dispersion, a' b' c', become smaller in the same proportion; and, therefore, the light from different points of the object is more and more separated on the receiving screen, and the image becomes first recognizable, then more and more distinct. But, in the mean time, the *quantity* of light is becoming less and less, and therefore the image fainter and fainter. If we suppose the hole to become a mathematical point, then one ray only passes from each point to the object, and goes to its own place in the image (Fig. 6, *B*), and the conditions of distinctness are fulfilled; but the image is now infinitely faint, and therefore invisible. If, now, we try to increase the brightness by increasing the size of the hole, in proportion as we get *brightness* do we lose *distinctness*. We can not get both at the same time.

Experiment.—Let a room with solid shutters be darkened; let one shutter have a hole of a few inches in diameter; cover the hole with an opaque plate of sheet iron, in which there is a very small hole, one tenth to one twentieth of an inch in diameter. If, now, a sheet of white paper be held a little way from the small hole, an inverted image of the external landscape will be seen on the sheet. If we increase the size of the hole, the image will be brighter, but also more blurred.

Illustrations.—Many simple experiments may be made illustrating this principle. A pinhole in a card will make an inverted image of a candle flame. When the sun is in eclipse, it may be examined without smoked glass, by simply allowing it to shine through a pinhole in a card upon a suitable screen. In the shade of a very thick tree-top the sun-flecks are circular like the sun; but during an eclipse they are crescentic, or even annular, according to the degree of obscuration. They are always images of the sun.

Property of a Lens.—Now a lens has the remarkable property of accomplishing both these apparently opposite ends, viz., brightness and distinctness at the same time. If an object, *a c*, be placed before a lens, *L* (Fig. 7), then *all* the rays diverging from any point, *b*, are

Fig. 7.



bent so as to come together again at the point b'. Of the divergent pencil, $b\ L\ L$, the central ray passes straight through without deviation; rays a little way from the central are bent a little; rays farther away are bent more and more according to their angle of divergence, so that they all meet at the same point, b'. Similarly all the rays proceeding from a, and falling on the lens, are brought to the same point, a', and from c to the point c', and so also for every intermediate point. Thus an image is formed which is both bright and very distinct if the receiving screen is suitably placed, i. e., at the exact place where the rays meet. The billions of rays from millions of points of the surface of the object are, as it were, sifted out by the law of refraction, and each safely conveyed to its own point in the image; so that, for every radiant point of the object, there is a corresponding focal point in the image. But it is evident that the screen must be suitably placed, for, if it be placed too near, at $S'\ S'$, the rays have not yet come together; if too far, at $S''\ S''$, the rays have already met, crossed, and again diverged. In both cases the image will be blurred.

Fig. 8.

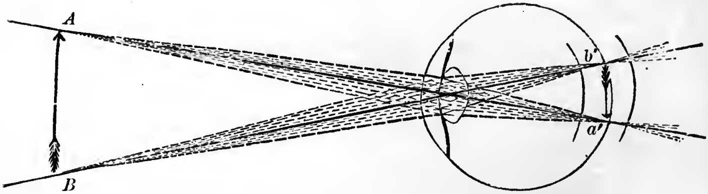


Diagram illustrating the Formation of an Image on the Retina.

In all dioptric instruments images are formed in this way. It is in this way that images are formed in the eye. In Fig. 8 it is seen that the diverging pencils, from points *A* and *B* of the object, which enter the pupil, are refracted by the lenses of the eye, and brought to a focus on the retinal screen at *a′ b′*. Now, since the rays from every intermediate point of the object will be similarly focused, we will have a perfect image of the object painted on the retina.

This fundamental fact may be proved in many ways by observations on the dead eye: 1. If the eye of an ox be taken from the socket, and the sclerotic carefully removed, so that the back parts of the eye are somewhat transparent, a miniature image of the landscape may be seen there; or, 2. If we remove the eyeball of a white rabbit, we will find that, on account of the absence of black pigment in the choroid of these albinos, the transparency of the coats of the eye enables us to see the image, even through the sclerotic, or much more distinctly if the sclerotic be removed; or, 3. We may remove all the coats of the dead eye and replace them by a film of mica—the image will be very distinct; or, 4. The image may be seen in the living eye by means of the ophthalmoscope.

By reference to the diagram, Fig. 8, it is seen that the central rays from all radiants cross each other in the lens. This point of ray-crossing is called the *nodal point.* It is a little behind the center of the lens.

CHAPTER II.

THE EYE AS AN OPTICAL INSTRUMENT.

The further explanation of the wonderful mechanism of the eye is best brought out by a comparison with some optical instrument. We select for this purpose the photographic camera. The eye and the camera: the one a masterpiece of Nature's, the other of human art.

We pass over, with bare mention, some obvious resemblances, in which, however, the superiority of the eye is evident: such, e. g., as the admirable arrangement of the lids for wiping and keeping bright while using, and for covering when not in use; also, the admirable arrangement of muscles, by which the eye is turned with the greatest rapidity and precision on the object to be imaged, so superior to the cumbrous movement of the camera for the same purpose. We pass over these and many other minor points to come at once to the main points of comparison.

Take, then, the eye out of the socket—the dead eye—and the camera without its sensitive plate—with only the insensitive ground-glass receiving plate. They are both now pure optical instruments, and nothing more. They are both contrived for the same purpose, viz., the formation of a perfect image on a screen properly placed.

Look into the camera from behind, and we see the inverted image on the ground-glass plate; look into the eye from behind, and we see also an inverted image on the retina. The end, therefore, is the same in the two cases. We now proceed to show that the means by which the end is attained are also similar.

1. The camera is a small, dark chamber, open to light only in front, to admit the light from the object to be imaged. It is coated inside with lampblack, so that any light from the object to be imaged or from other objects which may fall on the sides will be quenched, and not allowed to rebound by reflection, and thus fall on the image and spoil it. No light must fall on the image except that which comes directly from the object. So the eye also is a very small, dark chamber, open to light only in front, where the light must enter from the object to be imaged, and lined with dark pigment, to quench the light as soon as it has done its work of impressing its own point of the retina, and thus prevent reflection and striking some other part, and thus spoiling the image.

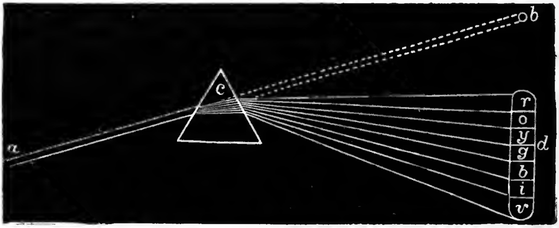
2. Both camera and eye form their images by means of a lens or a system of lenses. The manner in which these act in forming an image has already been explained (page 28). It is precisely the same in both cases. But lenses which form a perfect image are very difficult of construction. There are, especially, two main imperfections which must be corrected, viz., *chromatism* and *aberration.*

3. *Correction of Chromatism.*—In the image formed by a simple, ordinary lens, all the outlines of figures are found to be slightly edged with *rainbow hues.* If we look through such a lens at an object, the outlines of the object will be similarly edged with colors, especially

if the object lie near the margin of the field of the lens. This is explained as follows:

Ordinary sunlight, as every one knows, consists of many colors mixed together, the mixture producing the impression of *white.* If a beam of sunlight be made to pass through a glass prism, the beam is bent: but more, the different colors are *unequally* bent, so that they are separated and spread out over a considerable space. This colored space is called the spectrum. In Fig. 9 the straight beam, *a b*, is bent by the prism so as to become *a c d;* this is called *refraction.* But also the different colors are unequally bent; red is bent least and violet most, the other colors lying between these extremes; thus they are spread out over a considerable colored space. This *unequal* refraction is called *dispersion.* If we look through a prism at objects, we will find that the outlines of the objects will be edged with exactly similar colors. Now all refraction is accompanied by dispersion; therefore a simple, uncorrected lens always disperses, especially on the edges where the refraction is greatest; and, therefore, also, the images made by such a lens will be edged with color. Thus the light from the radiant *a* (Fig. 10), being white light, is dispersed; the violet rays, being more bent, reach a focus at *a′*,

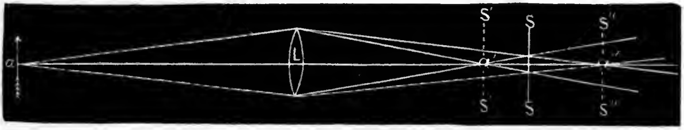
FIG. 9.



r–v, spectrum: *r*, red; *o*, orange; *y*, yellow; *g*, green; *b*, blue; *i*, indigo; *v*, violet.

but the red only at a'', the other colors at intermediate points. There is, therefore, no place where all the rays from the radiant come to a focus—there is no common focal point for the radiant a. The best place

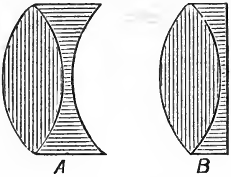
FIG. 10.



for the receiving screen would be $S\,S$, but even here there is no perfect focus. Evidently, therefore, the conditions of a perfect image are not fulfilled. This defect must be corrected. It *is* corrected in every good lens.

In order to understand how this is done, it must be remembered, first, that concave and convex lenses antagonize, and, if of equal refractive power, neutralize each other. Therefore, a combination of a double convex and a double concave lens, if of same material and of equal curvature, like Fig. 11, *A*, will produce no refraction, because the refraction produced in one direction by the convex lens is completely destroyed by refraction in the opposite direction by the concave lens. Such a combination will therefore make no image. In order that such a combination should make an image at all, it is necessary that the convexity should predominate over the concavity, as in Fig. 11, *B*. Again, it must be remembered that dispersion is not always in proportion to refraction. Some substances

FIG. 11.



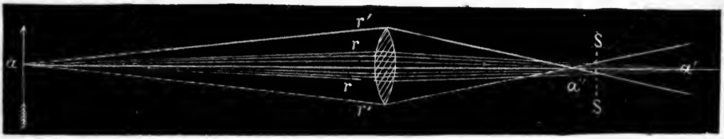
have a higher refractive power and a comparatively low dispersive power, and *vice versa.* This is the case with different kinds of glass.

Now, suppose we select a glass with excess of refractive over dispersive power for our convex lens, and one with excess of dispersive over refractive power for our plano-concave lens (Fig. 11, *B*), and cement these together as a compound lens: it is evident that these may be so related that the plano-concave lens shall entirely correct the dispersion of the convex lens without neutralizing its refraction, and therefore the combination will be a refractive, but not a dispersive, lens, and therefore will make an image without colored edges. Such a compound lens is called *achromatic.*

This is the way in which art makes achromatic lenses, and all good optical instruments have lenses thus corrected. Now, the lenses of the eye are apparently corrected in a similar manner. The eye consists of three lenses—the aqueous, the crystalline, and the vitreous. These have curvatures of different kinds and degrees: the aqueous lens is convex in front and concave behind; the crystalline is bi-convex; the vitreous is concave in front. As its convex outer surface can not be regarded as a refracting surface, since this is in direct contact with the screen to be impressed, it may be considered as a *plano-concave* lens. The refractive powers of the material of these are also different: that of the crystalline being greatest, and the aqueous least. The dispersive powers of these have not been determined, but they probably differ in this respect also. Thus, then, we have here also a combination of different lenses, of different curvatures, and different refractive, and probably dispersive, power, and for the same purpose, viz., correction of chromatism. It is an interesting historic fact that the hint for correction of chromatism by combination of lenses was taken from the structure of the eye by Euler, and afterward carried out successfully by Dollond. That the chromatism of the eye is substantially corrected is shown by the complete absence of colored edges of strongly illuminated objects, and the sharp definition of objects seen by good eyes. By close observation and refined methods, it has been recently shown that the chromatism of the eye is not perfectly corrected. It can be observed if we use only the extreme colors, red and violet.* But the degree of chromatism is so small as not to interfere at all with the accuracy of vision.

4. *Aberration.*—Another defect, much more difficult to correct, is aberration. The form of lens most easily made has a *spherical* curvature. But in such a lens there is an excess of refractive power in the *marginal* portions as compared with the *central* portions; an excess increasing with the distance from the center; therefore the focal point for marginal rays is not the same as for the central rays, but nearer. In Fig. 12 the marginal rays, $a\ r'$, $a\ r'$, are brought to a focus at a'', while the central rays, $a\ r$, $a\ r$, are brought to a focus at a'. The best place for the receiving screen would be at $S\ S$, between these; but even there the image would not be sharp. In such a lens there is no

FIG. 12.



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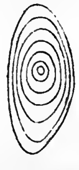
* Helmholtz, "Popular Lectures," p. 216.

common focal point for all the rays, and therefore the conditions of perfect image are not fulfilled—the image is blurred. This defect must be corrected. It is corrected in the best lenses.

The aberration may be greatly decreased by the use of diaphragms, which cut off all but the central rays; but in this case we get distinctness at the expense of brightness. This may be done when the light is very intense. Again, the aberration may be reduced by using several very flat lenses, instead of one thick lens. This plan is used in many instruments. But complete correction can only be made by increasing the refraction of the central portions of the lens, and this may conceivably be accomplished in two ways, viz., either by increasing the curvature of this part or by increasing its density, and therefore its refractive index. It is by the former method that art makes the correction. By mathematical calculation, it is found that the curve must be that of an ellipse. A lens, to make a perfect image, must not be a segment of a sphere, but of the end of an ellipsoid of revolution about its major axis. It is justly considered one of the greatest triumphs of science to have calculated the curve, and of art to have carried out with success the suggestion of science.

Art has not been able to achieve success by the second method. It is impossible so to graduate the increasing density of glass from the surface to the center of a lens as to correct aberration. Now, it is apparently this second method, or perhaps both, which has been adopted by nature. The crystalline lens increases in density and refractive power from surface to center, so that it may be regarded as consisting of ideal concentric layers, increasing in density and curvature until the central nucleus is a very dense and highly refractive spherule (Fig. 13). The surface of the cornea has the form of an ellipsoid of revolution about its major axis, and therefore doubtless contributes to the same effect. In looking at very near objects, the contraction of the pupil, also, by cutting off marginal rays, tends in the same direction. However the result may be accomplished, whether by one or by both methods, it is certain that in good eyes it is completely achieved, for the clearness of vision is wholly conditioned on the sharpness of the retinal image.

Fig. 13.



Section showing the Structure of the Lens.

It is probable that the peculiar structure of the crystalline lens described above has also another important use in the lower animals, if not in man. Dr. Ludimar Hermann[*] has shown that, in a homogeneous lens, while the rays from radiants near the middle of the field of view, i. e., nearly directly in front, are brought to a perfect focus, the rays from radiants situated near the margins of the field of view, i. e., of very oblique pencils, are not brought to a focus. Therefore the picture formed by such a lens is distinct in the central parts, but very indistinct on the margins. Now, this defect of a homogeneous lens, Dr. Hermann shows, is entirely corrected by the peculiar structure of the crystalline; therefore this structure confers on the eye the capacity of seeing distinctly over a wide field, without changing the position of the point of sight. This capacity he calls *periscopism*. We will hereafter, however, give reasons showing that this property of the crystalline can be of little value to *man*.

5. *Adjustment for Light.*—The delicate work done by the camera and by the eye requires a proper regulation

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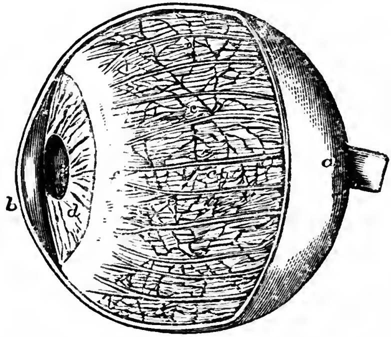
[*] "Archives des Sciences," vol. lxiii, p. 66. 1875.

of the amount of light. In both, therefore, we want some contrivance by which, when the light is very intense, a large portion may be shut out, and when the light is feeble, a larger portion may be admitted. In optical instruments this is done by means of diaphragms. In the camera we have brass caps with holes of various sizes, which may be changed and adapted to the intensity of the light. In the microscope we have a circular metallic plate, with holes of various sizes. By revolving this plate we bring a larger or a smaller hole in front of the lens.

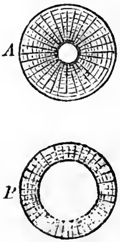
In the eye the same end is reached, in a far more perfect manner, by means of the iris. The iris (Fig. 14, *d*) is an opaque circular disk, with a round hole, the pupil, in the middle. The circumference of the disk is immovably fixed to the sclerotic at its junction with the cornea; but the margin of the circular hole, or pupil, is free to move. The disk itself is composed of two sets of contractile fibers, viz., the radiating and the

FIG. 14.



HUMAN EYE, ENLARGED, WITH PART OF CORNEA AND SCLEROTIC REMOVED.—*a*, sclerotic; *b*, cornea; *c*, choroid; *d*, iris; *e*, pupil; *f*, ciliary muscle. (After Cleland.)

FIG. 15.



SHOWING STRUCTURE OF IRIS.

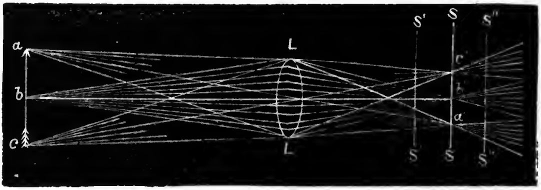
circular (Fig. 15). The radiating fibers converge from the outer margin of the iris as a fixed point, and take hold on the movable margin of the pupil, and, when they contract, pull open the pupil on every side, and thus enlarge it (Fig. 15, *B*). The circular fibers are concentric with the pupil, and are especially numerous and strong near the margin, forming there a band about one-twentieth of an inch wide. When they contract, they draw up the pupil, like a string about the mouth of a bag, and make it small (Fig. 15, *A*). We may regard the radiating fibers as *elastic*, and as contracting *passively* by elasticity when stretched; and the circular fibers as contracting *actively* under stimulus, like a muscle. Further, the circular fibers are in such sympathetic relation with the retina, that a stimulus of any kind, but especially its appropriate stimulus, light, applied to the latter, causes the former to contract, the extent of the contraction being of course in proportion to the intensity of the light. If, therefore, strong sunlight impresses the retina, the circular fibers immediately contract, the pupil becomes small, and a large portion of the light is shut out. When the light diminishes, as in twilight, the circular fibers relax, the previously stretched radiating fibers contract by elasticity, and enlarge the pupil. At night the pupil enlarges still more, in order to let in as much light as possible. Finally, if a solution of belladonna (which completely paralyzes the circular fibers) be dropped into the eye, the pupil enlarges so that the iris is reduced to a narrow dark ring.

Art, taking the hint from Nature, and striving to be not outdone, has recently constructed for the microscope a diaphragm somewhat on this plan. It is composed of many very thin metallic plates, partly covering each other, so arranged as to leave a polygonal hole in the middle, and sliding over each other in such wise that by turning a milled head in one direction they all move toward the central point and diminish the opening, while by turning in contrary direction they all move away from the center and make the hole larger. This is confessedly a beautiful contrivance, but how inferior to the admirable work of Nature!

As already stated (page 37), contraction of the pupil takes place not only under the stimulus of light, but also in looking at very near objects. The reason of this is, that correction of spherical aberration is thus made more perfect.

* 6. *Adjustment for Distance—Focal Adjustment.*—We have seen that a lens, properly corrected for chromatism and aberration, makes a perfect image. But the plate or screen which receives the image and makes it visible must be placed *exactly in the right place*, i. e., in the focus; otherwise the image will be blurred. We reproduce here (Fig. 16) the diagram on page 27, showing this. It is at once seen that, if the receiving plate is too near the lens, i. e., at S' S', the rays from any radiant of the object will not yet have come together at a focal point. If the receiving screen be too far from the lens, at S'' S'', then the rays moving in straight lines will have already met, crossed, and again spread out. It is evident that there is but one

FIG. 16.



* Explain here how the focus is diff. for diverg. rays + parallel rays. -

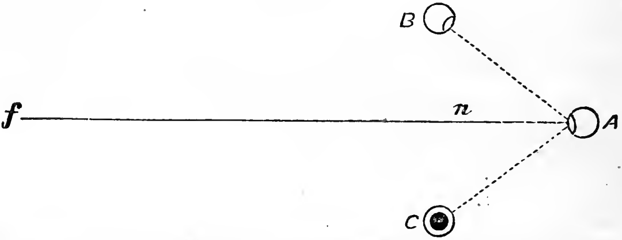
place where the image is perfect, viz., at the focal points, *S S.* Now, if this place of the image were the same for all objects at all distances, it would be only necessary to find that place, and fix the receiving plate immovably there. But the place of the image formed by any lens changes with every change in the distance of the object. As the object in front approaches, the image on the other side recedes from the lens. As the object recedes, the image approaches the lens. Therefore there must be an adjustment of the instrument for the distance of the object.

There are only two possible ways in which this adjustment can be made: Either (1st), the lens remaining unchanged, the screen must advance or recede with the image; or (2d), the place of the screen remaining the same, the lens must be changed so as always to throw the image on the immovable screen. The first is the mode of adjustment used in the camera, the opera-glass, the field-glass, and the telescope; the second is the mode usually used in the microscope. In the camera, for example, when the object comes nearer, we draw out the tube so as to carry the ground-glass plate a little farther back; when the object recedes, we slide up the tube so as to bring the receiving plate nearer the lens. So in the opera-glass we elongate the tube for near objects, and shorten it for more distant. In the microscope, on the contrary, the image is usually thrown to the same place in the upper part of the tube. If, therefore, the object approaches nearer the lens (as it does in higher magnification), we change the lens so as to throw the image to the same place.

How is this managed in the eye? It was long believed that the adjustment was on the plan of the camera. Now, however, it is known that it is rather on the plan of the microscope. It was formerly thought that, in looking at a near object, the straight muscles, acting all together, squeezed the eye about the equatorial belt, and increased its axial diameter—in other words, made it egg-shaped—and thus carried the retinal screen farther back from the lens. But now it is known that the retinal screen remains immovable, and the lens changes its form so as to throw the image to the same place.

Experiment.—This is proved in the following manner: A person is chosen with good, normal young eyes. The experimenter stands in a dark room, in front of the patient, *A*, with a lighted candle in his hand, a little to one side, as in Fig. 17, *C*, while his own point of observation is on the other side, *B*. If the observer now looks carefully, he will see in the eye of the patient three images of the candle-flame: first, one reflected from the surface of the cornea, which is by far the brightest (Fig. 18, *a*); second, one from the anterior surface of the crystalline, much fainter (Fig. 18, *b*); third, one from the posterior surface of the crystalline, the faintest of all, and very small (*c*). Further, it will be observed that the first and second are erect images,

FIG. 17.

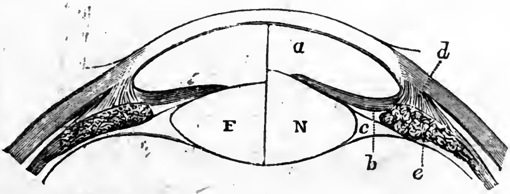


A, eye observed; *B*, eye of observer; *c*, section of candle flame; *f*, a distant point of sight, and *n* a near point of sight. (After Helmholtz.)

because reflected from a convex surface, while the third is inverted, because reflected from a concave surface. Now directing the patient to gaze on vacancy, or a distant point, *f*, Fig. 17, we observe carefully the position and size of these several images. Then, if by direction the patient transfers the point of sight to a very near point, *n*, without changing the direction, we observe that the images *a* and *c* do not change, but the image *b* changes its position and grows smaller. This image is reflected from the anterior surface of the crystalline. The *anterior surface* of the crystalline, therefore, *changes its form*. Again, the nature of the change of the image, viz., that it becomes smaller, shows that this anterior surface *becomes more convex*. By careful examination the iris, too, may be seen to *protrude* a little in the middle. Evidently, therefore, in adjusting the eye to very near objects, the crystalline becomes *thicker in the middle*, and pushes the pupil a little forward. In the accompanying diagram, Fig. 19, the crystalline lens is divided by a plane through the center. The right side, *N*, is adapted to near objects; the left, *F*, to distant objects.

FIG. 18.

FIG. 19.



F, lens adjusted to distant objects; *N*, to near objects; *a*, aqueous humor; *d*, ciliary muscle; *e*, ciliary process.

Theory of Adjustment.—Thus much may be considered certain. It is certain that in adjusting the eye for looking at very near objects, the lens becomes more convex. But the question, "How is this done?" is more difficult to answer. Helmholtz thinks it is done in the following manner:*

It will be remembered that the lens is invested by a thin, transparent membrane, which extends outward from its edge as a circular curtain, and is attached all around to the sclerotic, thus dividing the interior of the eye into two chambers—the anterior, filled with the aqueous, and the posterior, with the vitreous humor. It will be remembered, further, that this membrane is naturally drawn tight by the elastic rigidity of the sclerotic, and presses gently on the elastic lens, flattening it slightly. This is the normal passive condition, as when gazing at a distance. Now there are certain muscular fibers (ciliary muscle, Fig. 19, *d*) which, arising from the exterior fixed border of the iris just where it is attached to the sclerotic, run backward, radiating, and take hold upon the outer edge of the lens curtain. When these fibers contract, they pull forward the tense curtain to a smaller portion of the globe, and thus relax its tension. The relaxing of the tension of the curtain relaxes also the pressure of the capsule on the lens, which therefore immediately swells or thickens in proportion to the degree of relaxation. According to Helmholtz, then, *we adjust the eye to near objects by contraction of the ciliary muscle.* There are other views on this subject, but this seems the most probable.

The normal eye in a passive state is adjusted to infinitely distant objects. By change of the form of the lens, it can adjust itself to all distances up to about five

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* "Optique Physiologique," p. 150.

inches. The range of adjustment or of distinct vision is, therefore, within these limits. It is only at comparatively near distances, however, that the change is great. Between twenty feet and infinite distance the adjustment is almost imperceptible.

We see, then, that the mode of adjustment of the eye is somewhat like that of the microscope; i. e., the change is in the lens, not in the position of the receiving screen. Like the microscope, but how infinitely superior! The microscope has its four-inch lens, its two-inch lens, its one-inch lens, its half-inch lens, its quarter-inch, its tenth-inch, and even its fiftieth-inch lens. It changes one for another, according to the distance of the object. But the eye changes its *one lens*, and makes it a five-inch lens, a foot lens, a twenty-foot lens, a mile lens, or a million-mile lens; for at all these distances it makes a perfect image.

When you hold up your finger in front ~~befor~~
n object at some distance the finger
ll appear indistinct when the distant ob
distinct & vice versa — bec. wh. y are lookg
finger e rays o light fr any pt or distan
e refracted more th they shd b bec e lens
in condin for near rays & ∴ they cross in
nt or retina. Wh y are lookg at e distan
j e refractin ~~pow~~ or lens is less
shd b fr e ~~near~~ finger & ∴ e rays f
y pt or finger are not refracted
ough & come to a focus beyond e
ina — (Show this by diagram)

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plain how fr m e fact th e retina is
ncave images are not distorted as in
mera —

CHAPTER III.

DEFECTS OF THE EYE AS AN INSTRUMENT.

In the preceding chapter we have attempted to bring out, in a clear and intelligible form, the beautiful structure of the eye, by comparing it with the camera, and showing its superiority. But the eye of which we have been speaking is the normal or perfect eye. This normal condition is called *emmetropy*. The eye, however, is not always a perfect instrument. There are certain defects of the eye which are quite common. The principles involved in the construction of the normal eye may be still further enforced and illustrated by an explanation of these defects. Let it be observed, however, that these defects must not be regarded as the result of imperfect work on the part of Nature, but rather as the effects of misuse of the eye, accumulated by inheritance for many generations. They do not occur in animals, nor in the same degree in savage races; and most of them are also very rare in persons living for many generations in the country.

The most important of these defects are myopy and presbyopy.

Myopy, Brachymetropy, or Near-Sightedness.—The *normal or emmetropic eye* adjusts itself perfectly for all distances, from about five inches to infinity. It makes a perfect image of objects at all these distances. This is called *its range* of distinct vision. It has but one limit, viz., the nearer limit of five inches. Now in the passive state of the eye, as for instance in gazing on vacancy, or when the eye is taken out of the socket as a dead instrument, it is *prearranged* for perfect image of objects at an infinite distance. Its focus of parallel rays in a passive state is on the retina. For all nearer objects, a *voluntary* effort is necessary to throw the image on the retina, which effort is greater as the object is nearer, until it is limited at the distance of about five inches. The normal eye, therefore, is like a camera, which, when pushed up as much as possible, is arranged for making a perfect image of sun, or moon, or a distant landscape, but can by drawing the tube be adjusted to shorter and shorter distances up to five inches, but not nearer.

The myopic eye, on the other hand, is not prearranged for perfect image of distant objects. Its focus for distant objects (focus of parallel rays) is not on the retina, but in front of it. The refractive power of the lenses in their passive state is too great, or else the receiving screen (retina) may be regarded as too far back from the lens, viz., at $S'' S''$, Fig. 7, page 27. The rays have already reached focus, crossed, and again spread out before they reach the retina. An object must be brought much nearer before its perfect image will be thrown on the retina. Within this farther limit of perfect image, however, it *has its own range* of adjustment, like the normal eye. The range of the normal eye is from infinite distance to five inches. In the myopic eye the range may be from a yard to four inches, or from a foot to three inches, or from six inches to two inches, or even from three inches to one inch, according to the degree of myopy. The amount of ocular adjustment or change in the lens to effect these ranges is as great as for the normal range from infinite distance to five inches, but the latter is a far more useful range. The myopic eye, therefore, is like a camera which was never intended to be used for taking distant objects, which, therefore, when shortened to the greatest degree, is still too long in the chamber for distant objects, but is adapted only for near objects within a certain limited range.

It is evident, then, that, the defect of the myopic eye being too great refractive power of the lens in a passive state, this defect may be remedied by the use of *concave* glasses, with concavity just sufficient to correct the excess of refractive power, and therefore to throw the image of distant objects back to the retinal screen in the passive state of the eye. The eye then adjusts itself to all nearer distances, and becomes in all respects a normal eye. From the nature of the defect (structural defect), it is evident that the glasses must be worn *habitually*.

Presbyopy, or Old-Sightedness.—This defect is often called *long-sightedness*, or *far-sightedness;* but this is a misnomer, based on a misconception of its true nature. It is obviously impossible to have an eye more long-sighted than the normal eye, for this defines with perfect distinctness the most distant objects, such as the moon or the sun when the dazzling effect is prevented by smoked glass. It is usually regarded as a defect the reverse of near-sightedness. As near-sightedness is the result of *too great* refractive power in a passive condition, so this is supposed to be a *too small* refractive power in the same condition. As the myopic eye throws the focus of parallel rays in front of the retina, so it is supposed the presbyopic eye throws the focus of parallel rays behind the retina, because the retina is too near the lens, at $S' S'$, Fig. 7, page 27. It is further supposed that the change which takes place with age is a flattening, and therefore a loss of refractive power, of the lenses of the eye. It is constantly asserted, therefore, that the myopic eye may be expected to become normal with age.

Now this view of the nature of presbyopy is wholly wrong. The presbyopic eye sees distant objects perfectly well, and precisely like the normal eye. *Its passive structure is therefore unaltered.* It makes a perfect image of distant objects on the retina, like the normal eye. Its focus of parallel rays is *on* the retina, not behind it. It is therefore normal in its passive state, or in its structure. The defect, therefore, consists not in a change of the structure which originally adapted it to the imaging of distant objects, but in the loss of *power to adjust for near objects.* And this loss of adjusting power is, again, probably the result of loss of the elasticity of the crystalline lens. In the normal young eye, when the ciliary muscle pulls forward the lens curtain, and thus relaxes its tension, the lens by its elasticity swells and thickens, and becomes more refractive. In the presbyopic eye, the ciliary muscle pulls, and the curtain or capsule relaxes its tension, in vain; the lens, for want of elasticity, does not swell out. Therefore the remedy for presbyopy is the use of convex glasses, *not habitually*, not in looking at distant objects, but only in looking at or imaging near objects. The putting on of convex glasses does not make the presbyopic eye normal, as the use of concave glasses makes the myopic eye; therefore they can not be worn habitually. In looking at near objects, it uses glasses;

in looking at distant objects, the glasses are removed. Myopy is a *structural* defect; presbyopy is a *functional* defect. One is a defect of prearrangement of the instrument; the other is a loss of power to adjust the instrument. To compare with the camera again: the presbyopic eye is like a camera which was originally arranged for distant objects, and by drawing the tube could be adjusted for near objects also, but, through age and misuse and *rust*, the draw-tube has become so stiff that the apparatus for adjustment no longer works. It still operates well for distant objects, but can not be adjusted for nearer objects. If we desire to image a near object in such a camera, obviously we must supplement its lens with another convex lens.

From what has been said it is evident that the myopic eye does not improve with age, and finally become normal, as many suppose. Myopic persons continue to wear glasses of the same curvature until sixty or seventy years of age. I have never known a myopic person who discontinued the use of glasses as he grew older. The same change, however, takes place in the myopic as in the normal eye, i. e., the *loss of adjustment.* In all young eyes there is a range of adjustment between a nearer and a farther limit; in the normal eye it is between five inches, near limit, and infinite distance, the farther limit (if limit it can be called); in the myopic eye the nearer limit may be two inches, the farther limit four inches, or it may be between three and six inches, or four inches and one foot, according to the degree of myopy. Now, with advancing age, the nearer limit, i. e., the limit of adjustment, recedes. In the normal eye it is first eight inches, then one foot, then three feet, etc., until, when adjustment is entirely lost, it reaches the farther limit, and there is but one distance of distinct vision; but the farther limit, i. e., structural limit, does not change. So also in the myopic eye, with advancing age, the nearer limit or limit of adjustment recedes, but not the farther limit or structural limit. This remains the same. But, as this was always too near for useful vision, glasses must still be worn. Thus it is evident that myopy and presbyopy may exist in the same individual.

In extreme old age, when the tissues begin to break down, it is probable that some flattening of the eye may take place. To such persons it would be necessary to wear convex glasses, even for distant objects. But this is not ordinary presbyopy. In fact, it is probable that most of such cases belong to the next category.

Hypermetropy.—We have dwelt on the two most common defects of the eye, but there are others less common, which must be briefly characterized. Hypermetropy is the true opposite of myopy. Like the latter, it is a structural defect, but in the opposite direction. In this case the lens is not sufficiently refractive for the length of the chamber, or the receiving screen is too near (at $S' S'$, Fig. 7) for the refractive power of the lens. Therefore the focus of parallel rays is behind the retina in a passive state of the eye. The hypermetropic eye when young usually sees well at a distance, but not near at hand, and therefore it is apt to be confounded with presbyopy. The reason is, that a slight adjustment adapts the eye for perfect retinal image of distant objects; but the near limit of its range of adjustment is much farther off than in the normal. When, however, the hypermetropic eye loses its power of adjustment with age, then even distant objects can not be seen distinctly. Such persons, therefore, while young, should habitually wear slightly convex glasses, which make their eyes normal. When they grow old, they are compelled to have *two pairs of glasses*, one for distant objects and one for near objects; one for walking and one for reading. The hypermetropic eye may be compared to a camera which, when entirely pushed up, is too short for the imaging of any objects whatever. By drawing, it may be adjusted for distant objects, but not for near objects.

Astigmatism.—The form of a perfect eye is that of a spheroid of revolution about the optic axis. Its refraction in a horizontal and a vertical plane will be equal. This is necessary to bring all rays to a perfect point at the same distance. But eyes are found in which the horizontal curvature of the cornea or of the crystalline, or both, is different from the vertical curvature. Such eyes are said to be astigmatic, because the rays from any radiant are brought to a focal *line*, instead of a focal *point*. A very slight degree of astigmatism is not uncommon, and often exists unknown to the patient.

CHAPTER IV.

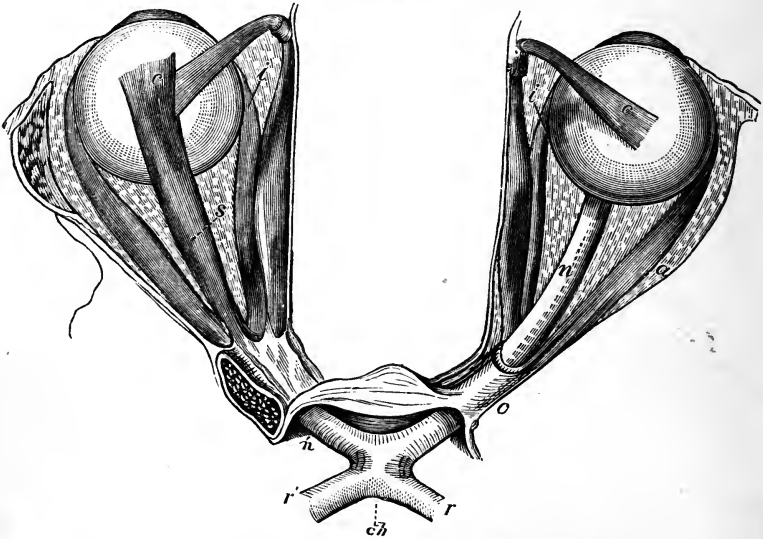
EXPLANATION OF PHENOMENA OF MONOCULAR VISION.

SECTION I.—STRUCTURE OF THE RETINA.

We have thus far treated of the eye, and compared it with the camera, purely as an optical instrument, contrived to form an image upon a receiving screen suitably placed. We have also treated of the defects of the eye, as much as possible, from the same physical point of view as defects of an instrument. But in both the camera and the eye the image is only a means to accomplish a higher purpose, viz., to make a photographic picture in the one case and to accomplish vision in the other. We have thus far spoken as much as possible only of an *insensitive* screen, the ground-glass plate in the one case and the dead retina in the other. But in both, when accomplishing their real work, we have a *sensitive* screen, in which wonderful changes take place, viz., the iodized plate in the one and the living retina in the other. In order to understand the real function of the eye in the living animal, it is necessary that we study the structure and functions of the *retina.*

Structure of the Retina.—The retina, as already stated, page 22, is a thin membranous expansion of the optic nerve. These nerves, arising from the optic lobes of the midbrain, appear first beneath the base of the brain as the optic roots, *r r′*, Fig. 20, converge, unite, and partially cross their fibers at the optic chiasm, *ch;* then, again diverging, enter the conical eye-sockets a little to the interior of the point; then pass through the midst of the fatty cushion behind the eye, surrounded by the diverging recti muscles, and finally penetrate the sclerotic at a point about one eighth of an inch to the inside of the axes; then spread out all over the interior of the ball as an innermost coat, immediately in contact with the vitreous humor, and extend as far forward as the ciliary processes, or nearly to the iris. The wide extent of this expansion and its hollow con-

Fig. 20.

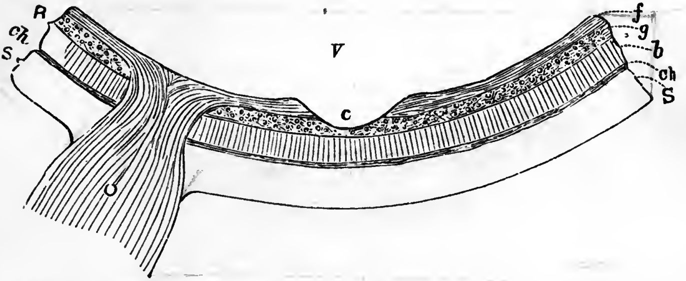


A View of the Two Eyes, with Optic Nerves.—*ch*, optic chiasm; *r r′*, nerve-roots; *n* and *n′*, right and left optic nerves. (After Helmholtz.)

cave form are necessary to give wideness to the field of view. By this means rays from objects, not only in front but far to the right and left, above and below, fall upon and impress the retina.

The thickness of this nervous expansion is about one hundredth of an inch, or about the thickness of thin cardboard, at the bottom or thickest part, but thins to one half that amount on the anterior margins; yet, under the microscope, a section through the thickness shows that it is very complex in its structure, being composed of several very distinct layers. We may first represent it on a smaller scale as composed of three principal layers: First, the innermost layer, *f*, Fig. 21, in contact with the vitreous humor, *V*, is composed wholly of fine interlaced fibers of the optic nerve. This nerve, *o*, is seen to pierce the sclerotic and the other layers of the retina, and then to spread out as an innermost layer. Second, outermost of all, and therefore in contact with the choroid, *ch*, is a remarkable layer, composed of cylindrical rods, like pencils set on end. This is called the *bacillary* layer (*bacillum*, a small rod), or

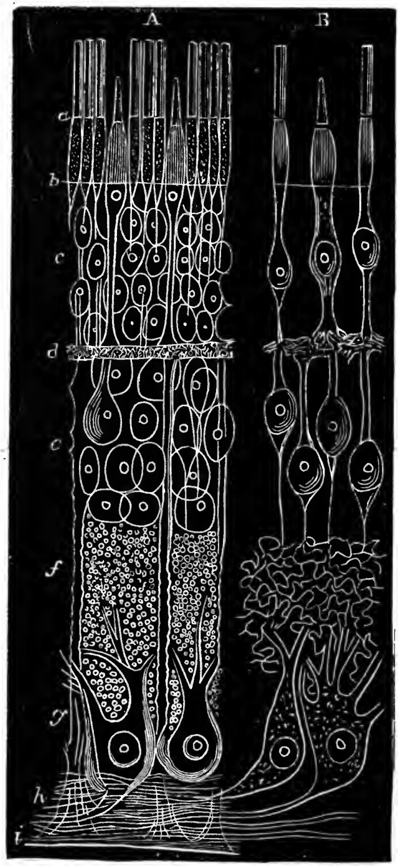
FIG. 21.



GENERALIZED SECTION OF RETINA, ETC.—*O*, optic nerve; *S*, sclerotic; *ch*, choroid; *R*, retina; *b*, bacillary layer; *g*, granular and cellular layer; *f*, fibrous layer; *V*, vitreous humor; *c*, central spot.

layer of rods, *b*. Third, between these is found a layer composed of granules and nucleated cells, *g*. This may be called for the present the granular and nuclear layer.

Fig. 22.



Enlarged Section of Retina (after Schultze).—*A*, general view; *B*, nervous elements; *a*, bacillary layer; *c*, external nuclear layer; *d*, external granular layer; *e*, internal nuclear layer; *f*, internal granular layer; *g*, ganglionic layer; *h*, fibrous layer, consisting of fibers of optic nerve.

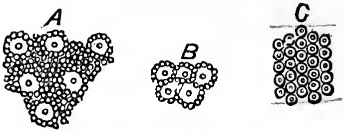
Further, it will be seen that these layers exist, all three, in every part of the retina except two spots. These are the spots where the optic nerve, *o*, enters, and the central spot, *c*, which is in the axis of the eye. Where the optic nerve enters, of course, no other layer can exist except the fibrous layer. In the central spot the fibrous layer is wholly wanting, and the granular and nuclear layer is almost wanting, so that the retina is here almost reduced to the bacillary layer. For this reason this spot forms a depression in the retina.

But the extreme importance of the retina requires that these layers be examined more closely. For this a much greater enlargement is necessary. Fig. 22 represents such enlargement. The fibrous layer, *h*, requires no further description; but the granular and nuclear layer is seen to be composed of two distinct layers of small granules, *d* and *f*, and two layers of large nucleated cells, *c* and *e*, and a layer of very large nucleolated cells, *g*, from which go out branching fibers. These are multipolar cells, or ganglia. It is further seen that the bacillary layer is composed of two kinds of elements, viz., slender cylindrical rods and larger cone-like bodies. These are called *rods* and *cones*. It is seen, still further, that all these different elements of the retina are in continuous connection with each other, and with the fibers of the optic nerve.

The bacillary layer is of the extremest interest. It consists mostly of rods, but among these are distributed the larger cones, as in Fig. 23, *A*. As we approach the central spot the cones become more numerous, as seen in *B*. In the *depression* of the central spot (*fovea centralis*) we find only cones, and these are of much smaller size than those in other parts of the retina, as seen in *C*. The rods are about $\frac{1}{350}$ inch in length and

$\frac{1}{14000}$ inch in diameter. The cones are shorter and about three times thicker than the rods, except in the central depression, where they are nearly as small as the rods, being there only $\frac{1}{10000}$ inch in diameter. In this spot, therefore, there are probably no less than one million cones in a square $\frac{1}{10}$ inch.

Fig. 23.



Bacillary Layer, viewed from the Outside Surface.—*A*, appearance of usual surface; *B*, appearance of surface of the raised margin of yellow spot; *C*, surface of central spot.

Distinctive Functions of the Layers.—As the distinctive functions of the several sub-layers of the middle layer (granular and nuclear) are unknown, we will treat of only the three layers—inner, middle, and outer. The outer layer of rods and cones (bacillary) is undoubtedly the true receptive layer, which corresponds to the iodized film of the sensitized plate of the camera. These rods and cones receive and respond to the vibrations of light; they co-vibrate with the undulations of the ether. The inner or fibrous layer conducts the received impression to the optic nerve; for each rod and cone is connected by a slender thread, continuous with nucleated cells of the granular layer and a fiber of the fibrous layer. The fibrous layer may, in fact, be regarded as a layer of conducting threads coming from the rods and cones, which threads are then gathered into a cord or cable, the optic nerve, which in its turn finally conducts the impression to the brain. The function of the middle layer is more obscure; but nucleated nerve-cells, and especially multipolar cells, are always generators or originators of nerve-force. They evidently have an important function. They probably act as little nerve-centers; and many unconscious, involuntary, or reflex acts of vision are probably performed by their means, without referring the sensation to the brain.

The manner in which the whole apparatus operates is briefly as follows: The light penetrates through the retina until it reaches the outer layer of rods and cones. These are specially organized to respond to or co-vibrate with the undulations of light. These vibrations are carried through the connecting threads to the fibrous layer, then through the fibers of this layer to the optic nerve, then along the fibers of the optic nerve to the gray matter of the brain, where they finally determine changes which emerge into consciousness as the sensation of light.

That we have correctly interpreted the function of the layer of rods and cones is rendered probable not only by its very remarkable and complex structure, adapting it to responsive vibrations, but also by the peculiar properties of two spots on the retina on which all the layers do not co-exist. Just where the optic nerve enters, as shown in Fig. 21, page 55, the bacillary layer is necessarily wanting, and it is the only spot in which this is the case. *Now, this spot is blind* (see page 78). Again, just in the axis of the globe, or what might be called the south pole of the eye, is the central spot or central pit. In this spot is wanting the fibrous layer and the whole of the middle layer, except the multipolar cells. The bacillary layer is here, therefore, directly exposed to the action of light. Now, this is the most sensitive spot of the retina.

Perception of Color.—Color, like musical pitch, consists of an infinite number of kinds and shades; but these may be reduced to a few primary kinds, by the mixture of which the intermediate shades may be supposed to be made. Newton made seven primary colors in the solar spectrum; but though these, and indeed many more, may be considered distinct from the physical point of view, since they are the result of different rates of ethereal vibration, yet they can not be all considered as primarily distinct *sensations*. Brewster reduced all color-sensations to three primary, viz., red, yellow, and blue. Young made them red, green, and violet. This latter view is adopted by Helmholtz and most modern writers.

Recently, however, Hering * has reinvestigated the whole subject with great acuteness, from the purely physiological instead of physical point of view, and arrives at different results. Hering includes *white* and *black* among his primary color-sensations, making six in all. But, leaving out these as belonging rather to the category of shades or *nuances*, according to Hering there are four and only four primary color-sensations essentially distinct from each other, viz., red, yellow, green, and blue. Aside from all physical considerations, undoubtedly this is true. These four colors are essentially distinct and irresolvable into any mixture of others. Again, according to Hering, these four are reducible to two complementary pairs, viz., red and green on the one hand, and yellow and blue on the other. This is also undoubtedly true. Finally, according to Hering, complementary colors are the result of *opposite* affections of the retina, so that there are only two essentially distinct color-affections of the retina, which, with their opposites, produce the two pairs of complementary colors: the one with its opposite produces red and green;

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* Hering, "Zur Lehre von Licht-Sinne," Wien, 1878.

the other with its opposite, yellow and blue. This, though more doubtful, seems a probable cause of complementariness.

Theory of Color-Perception.—Color-perception is undoubtedly a simple perception, and irresolvable into any other. It must, therefore, have its basis in retinal structure. Since light is perceived by co-vibration of retinal elements, and since the different colors have different rates of vibration, there must be a corresponding structure of the retinal elements, by means of which they co-vibrate with each of these colors. In the ear different rates of aërial vibration (musical pitch) are perceived by means of rods of different lengths (rods of Corti), which co-vibrate, each with its own pitch. It seems probable, therefore, that different rods or cones co-vibrate with different rates of ethereal undulations, i. e., with different colors. This is the commonly received view, brought forward first by Young. It is supposed that there are three kinds of rods or cones, which severally co-vibrate with the three primary colors of Young. One kind responds to the slower vibrations of red, another kind to those of green, and still another to the more rapid vibrations of violet. When two kinds vibrate, intermediate colors are perceived. When all vibrate together, then white light is perceived. Or, to express it differently, intermediate colors produce vibration of two kinds, white light of all kinds, of rods. Or, if we adopt the theory of Hering in regard to the primary colors, one kind of rod or cone responds to red and green, another kind to yellow and blue.

Very recently Stanly Hall has proposed a theory which seems even more probable.* He believes that color is perceived by the *cones* alone; further, that

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* "American Academy of Science and Art," vol. xiii, p. 402 (1878).

different parts of the same cone vibrate with different degrees of rapidity, and therefore respond to different colors, and that the *conical form* is adapted for this purpose. In order to gain clearer conception, we may imagine each cone to be made up of a number of buttons of graduated sizes joined together. These buttons, on account of their different sizes, would vibrate with different degrees of rapidity, and therefore co-vibrate with different colors. White light, he supposes, vibrates the whole series; red light, the thicker, and violet, the thinner, portion of the series; or, taking Hering's view of the primary colors, we may imagine that red and green rays affect one portion, and yellow and blue rays another portion, of the same cone.

The subject of the mechanism of color perception, however, is yet in the region of speculation, though probably of profitable speculation. To pursue it any further would be unsuited to the character of this treatise.

Daltonism, or Color-Blindness.—Many persons lack a nice discrimination of shades of color. Such persons see colors perfectly well, but, from want of attention or culture, have not learned to nicely discriminate and name them. This must not be confounded with *color-blindness.* The color-blind do not see some colors as colors at all. The defect is not one of culture, but of *sensation.* We can best explain it by comparing the eye and ear.

The limits of the perception of sound-vibrations are very wide, viz., more than eleven octaves. The limits of perception of light-vibrations are far more restricted, viz., only a little more than one octave. Now in many ears the extreme limits are not perceived; but this is not considered a defect, because there is no special use for the extremest range. So in the eye. Even the narrow limits of the normal eye are sometimes not reached; but in this case the usefulness of the whole range makes it a serious defect. This is color-blindness. In the ear the vibrations most commonly unperceived are at the upper end of the scale. In the eye it is usually the lower end of the scale which is defective, viz., red, or red and green. The color-blind see yellow and blue, but not red and green.

This defect was first brought to scientific notice by the celebrated chemist Dalton, and after him has often been called Daltonism. The peculiarities of Dalton's vision were carefully investigated by Sir John Herschel, and the first scientific explanation was given by him. Adopting the view of Young of three primary colors, Herschel regarded normal vision as *trichromic*, but the vision of Dalton as *dichromic*, the red being wanting. This view certainly explained the most striking phenomena of color-blindness, but it does not explain the fact that green is wanting as well as red. As shown by Pole * (who is himself color-blind), the phenomena are far more perfectly explained on Hering's view of the primary colors; and conversely, the phenomena of color-blindness are a powerful argument in favor of Hering's view. Of the two pairs of complementary colors of Hering, one pair, viz., the red-green, is wanting in the color-blind, while the other pair, yellow-blue, is perceived as in normal vision. The colors and shades, therefore, which are perceived by the color-blind are: 1, black and white, and all intermediate shades of gray; 2, yellow in all its shades; and, 3, blue in all its shades. A *pure* red seems to them a dark gray; but if mixed with yellow, as

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* "Nature," 20, pp. 477, 611, 637 (1879); "Contemporary Review," May, 1880.

are most reds, it appears yellow mixed with gray, or a *kind of brown;* or if mixed with blue (purple), it appears as blue mixed with gray, or *slate-blue.* A *pure* green appears simple *gray;* a yellow-green, yellow mixed with gray—i. e., *brown;* and a blue-green, *slate-blue.*

The cause of this defect of vision is, of course, a defect of retinal structure. If we admit that the rods and cones are the responsive elements, and that different kinds of rods or cones respond to different primary colors, then in the retina of the color-blind the rods or cones responding to red and green are wanting; or, by Hall's theory, the cones are so shaped that they respond to only one complementary pair, viz., to yellow and blue.

SECTION II.—FUNCTION OF THE RETINA, AND EXPLANATION OF THE PHENOMENA OF MONOCULAR VISION.

There is a certain peculiarity in the general function of the retina, optic nerve, and associated brain apparatus, which must now be explained and clearly apprehended, in order to understand the phenomena of vision.

Law of Outward Projection of Retinal Impressions.—An image is formed on the retinal screen. We have seen that the whole object of the complex arrangement of lenses placed in front of the retina is the formation of images. But we do not see the retinal images. We do not see anything *in the eye*, but something outside in space. It would seem, then, that the retinal image impresses the retina in a definite way; this impression is then conveyed by the optic nerve to the brain, and determines changes there, definite in proportion to the distinctness of the retinal image; and then the brain or the mind refers or projects this impression outward into space as an *external image, the sign and facsimile of an object* which produces it. We shall see hereafter how important it is that we regard what we see as *external images*, the signs of objects which produce them, and these external images themselves as projections outward of retinal images.

This law of outward projection is so important that we will stop a moment to show that it is not a new law specially made for the sense of sight, but only a modification of a general law of sensation. After doing so, we will proceed to illustrate by many phenomena, so as to fix it well in the mind.

Comparison with Other Senses.—The general law of sensation is, that irritation or stimulation in any portion of the course of a sensory fiber *is referred to its peripheral extremity.* Thus, if the sciatic nerve be laid bare in the upper thigh, and then pinched, the pain is felt, not at the part injured, but at the termination of the nerve in the *feet and toes.* If the ulnar nerve be pinched in the hollow on the inner side of the point of the elbow, pain is felt in the *little and ring fingers,* where this nerve is distributed. In amputated legs, as is well known, the sense of the presence of a foot remains, and often severe neuralgic pains are felt in the feet and toes. The pain, which in this case is caused by a diseased condition of the nerves at the point of amputation, is referred to the place where the diseased fibers were originally distributed. In nerves of *common sensation*, therefore, injury or disease, or stimulation of any kind in any part, is referred to the peripheral extremity of the nerve-fibers. Now the peculiarity of the optic nerve is, that it refers impressions not to its peripheral extremity only, but *beyond into space.*

But when we find great differences in the functions of tissues, such as occur in this case, we can generally find the steps which fill up the gap. A thoughtful comparison of the phenomena of the different senses will, we believe, reveal these steps. We repeat here what has already been said in a general way on page 13. Commencing with the lowest of the specialized senses, the gustative, an impression on the nerves of taste is referred, as in the case of common sensory fibers, to their peripheral extremity: the sensation is *on the tongue.* In the case of the olfactive, we have a sensation still at the peripheral extremity, i. e., *in the nose*, but also a reference to an external body at a distance as its cause. Here the objective cause and the subjective sensation are separated, and both distinct in the mind. In the case of the auditive nerve, the sensation is no longer perceived, or at least is very imperfectly perceived, in the ear, but is nearly wholly objective, i. e., referred to the distant sounding body. Finally, in the case of the optic nerve, the impression is so wholly projected outward that the very reminiscence of its subjectivity is entirely lost. We are perfectly unconscious of any sensation in the eye at all.

Illustrations of this Property.—We will now try to make this property clear by many illustrative experiments.

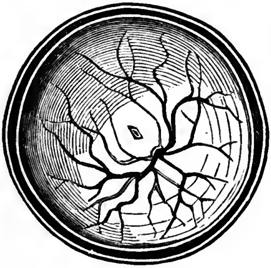
Experiment 1.—If the retina or the optic nerve in any portion of its course were irritated in any way, by pinching, by scratching, or by electricity, we should certainly not *feel any pain* at all, but *see* a flash of light. But where? Not at the peripheral extremity only, not *in the eye*, but beyond *in the field of view.* Of course, this experiment can not be easily made. It has been made, however, by passing a spark of electricity through the head or through the eye in such wise as to penetrate the retina or traverse the optic nerve. The phenomenon has also been observed in cases of extirpation of the eye at the moment of section of the optic nerve. (Helmholtz.)

Experiment 2. Phosphenes.—Press the finger into the internal corner of the eye: you perceive a brilliant colored spectrum *in the field of view* on the opposite or external side. The spectrum thus produced has a deep steel-blue center, with a brilliant yellow border, and reminds one of the beauty spots on a peacock's feather or a butterfly's wing. Remove the pressure to any other part, and the spectrum moves also, but retains its opposite position in the field of view. In this familiar experiment the pressure indents the sclerotic and causes a change or irritation on the forward portion of the retina; and any change whatever on the retina is always referred directly outward at a right angle to the point impressed, and therefore to the opposite side of the field of view. These colored spectra have been called phosphenes.

Experiment 3. Muscæ Volitantes.—If we gaze on a white wall or ceiling, or, still better, on a bright sky, we see indistinct motes floating about in the field of view on the wall or sky, and slowly gravitating downward. Sometimes they are undulating, transparent tubes, with nucleated cells within; sometimes they are like inextricably tangled threads, or like matted masses of spider's web; sometimes they are slightly darker spots, like faint clouds. They are called *muscæ volitantes*, or flying gnats. What are they? They are specks or imperfections in the transparency of the vitreous humor. As fishes or other objects floating in midwater of a clear lake on a sunny day cast their shadows on the bottom ooze, even so these motes in the clear medium of the vitreous humor, in the strong light of the sky, cast their shadows on the *retinal bottom.* Now, as already said, all changes in the retina, of whatever kind, whether produced by images, or shadows, or mechanical irritations, are projected outward into the field of view, and appear there as something visible.

Experiment 4. Purkinje's Figures.—Stand in a dark room with a lighted candle in hand. Shutting the left, hold the candle very near the right eye, within three or four inches, obliquely outward and forward, so that the light shall strongly illuminate the retina. Now move the light about gently, upward, downward, back and forth, while you gaze intently on the wall opposite. Presently the field of view becomes dark from the intense impression of the light, and then, as you move the light about, there appears projected on the wall and covering its whole surface a shadowy, ghost-like image, like a branching, leafless tree, or like a great bodiless spider with many branching legs. What is it? It is an exact but enlarged image of the *blood-vessels of the retina* (Fig. 24). These come in at the entrance of the optic nerve, ramify in the middle layer, and therefore in the strong light cast their shadows on the bacillary layer, of the retina. The impression of these shadows is projected outward into

FIG. 24.



INTERNAL VIEW OF THE RETINA, showing the retinal vessels ramifying over the surface, but avoiding the central spot. (After Cleland.)

the field of view, and seen there as an enlarged shadowy image. These have been called Purkinje's figures, from the discoverer.

Experiment 5. Ocular Spectra.—Look a moment steadily at the setting sun, and then, turning away the eye, look elsewhere—at the sky, the ground, the wall: a vivid colored spectrum of the sun (or many of them, if the eye has not been steady while regarding the sun) is projected into the field of view, and follows all the motions of the eye. This spectrum, on a bright ground, like the sky, to my eye is first green, then blue, then purple, and so gradually fades away. The spectrum is equally seen when the eye is shut; but then, being projected on a dark ground, the color is apt to be complementary to that of the same spectrum seen against the bright ground of the sky. It is first blue, then yellow, then green, and so fades. The explanation is obvious. The strong impression of the image of the sun on the retina induces a change which lasts some time; but every change in the retina appears, by projection, in the field of view.

This experiment may be made in an infinite variety of ways. If at night we gaze steadily at a candle- or lamp-flame, or flame of any kind, and then turn away and look at the wall, we see a vivid colored spectrum of the flame, which gradually changes its color and fades away. In my own case, on shutting the eyes, the spectrum is first bright yellow, with deep-red border and dark olive-green corona; then it becomes greenish-yellow, and then green with red border, then red with indigo border, and so fades away. With the eyes open the changes are slightly different, and in some stages are complementary to the preceding. Again, if we look a moment through a window at a bright sky, and then quickly turn the eye to the wall, we will see a faint spectrum of the window with all its bars projected against the wall. If we look intently and steadily at any object strongly differentiated from the rest of the wall of a room, as a small picture-frame or a clock, then look to some other part of the wall, the spectrum of the object will be seen on the wall and follow the eye in its motions. This experiment succeeds best when we are just waked up in the morning, and while the retina is still sensitive from long rest.

The experiment may be varied thus: Lay a small patch of vermilion red—such as a red wafer—on a white sheet of paper, and gaze steadily at it in a strong light for a considerable time, and then turn the eye to some other part of the paper. A spectrum of the wafer will be seen, because every difference in the retina will appear as a corresponding difference in the field. It will be observed, also, that the spectrum will be bluish-green, i. e., complementary to the red of the object. The reason seems to be that the long impression of the red produces a profounder change, or fatigue, in those rods or cones, or those portions of the cones, which co-vibrate with red; therefore, when we look elsewhere, of the different colors which make up white light, the retina is least sensitive to red, and therefore the other rays will predominate. Now these other rays, which with red make up white light, are what are called complementary to red. A mixture of these makes a bluish-green. It is difficult, however, to account for all the phenomena of the colors of spectra by this "*law of fatigue.*"

Complementary spectra may be still more beautifully seen by gazing on the brilliant contrasted colors of a stained-glass window, and then turning the eyes on a white wall. The whole pattern of the window will be distinctly seen in complementary colors.

Let it be observed here how differently spectral images behave from objects. When we move the eyes about, the images of objects move about on the retina, but the objects seem to remain unmoved. Spectral impressions on the retina, on the contrary, remain in the same place, and therefore their external images follow the motions of the eye.

We are now prepared to generalize from these observations. It is evident that what we call the field of view is naught else than the *external projection into space of retinal states.* All variations of *state* of the one, whether they be images, or shadows, or mechanical irritation, whether they be normal or abnormal, are faithfully reproduced as corresponding variations of *appearances* in the other. This sense of an external visual field is ineradicable. If we shut our eyes, still the field is there, and still it represents the state of the retina. With the eyes open, we call it the *field of view*, filled with objects; with the eyes shut, it is the *field of darkness*—visible, palpable darkness, without visible objects. The one is the outward projection of the active state of the retina, crowded with its retinal images; the other is the outward projection of the comparatively passive state of the retina, without definite images. When we shut our eyes, or stand with eyes open in a perfectly dark room, the field of darkness is an actual visible field, the outlines of which we can, at least imperfectly, mark out. It is wholly different from a simple absence of visual impression. We see a dark field in front, but nothing at all behind the head. The dark field is also quite different from *blackness.* If we must describe it as of any color, we should say that it is a dark grayish or brownish field, full of irregular, confused, and ever-shifting lines and cloudings. If the retina has been previously strongly impressed, spectra are seen on this dark background when the eyes are shut. When the eyes are open, the same spectra are seen on the bright ground of the sky or wall, and the difference of the background makes the difference of the color of the spectra in the two cases.

Now the same inherent activity of the retina which produces the sense of a dark field with its confused markings and cloudings, will also, under certain circumstances of peculiar sensitiveness of the retina, as after complete rest in the early morning, give rise spontaneously to more definite spectra, often of beautiful colors. I have often, in bed in the morning, watched with eyes shut these splendid spectra, consisting of a colored patch surrounded with a border of complementary color, each color closing in on the center and so vanishing, while another border commences on the outside to close in in the same way. Thus, just as impressions or images made *normally* on the retina by actual objects from without are projected into the field of view and seen there as the *true* signs of objects, even so impressions made on the retina *abnormally* from *within*, by the mind or imagination, are also sometimes projected outward, and become the *delusive* signs of external objects having no existence. It is thus that the diseased brain gives rise to delusive visual phenomena.

Corresponding Points, Retinal and Spatial.—Further, it is evident that every point—every rod or cone—in the retina has its invariable correspondent in the visual field, and *vice versa*. Moreover, since the central ray of the pencil of every radiant point in the external world passes through the nodal point of the crystalline lens, it is evident that these lines must cross each other there. In other words, the lines forming correspondent points in space and on the retina cross each other in the nodal point, and therefore the positions of these correspondent points, external and internal, are completely reversed. Thus not only are the retinal images inverted, but the relative positions of these images are inverted, and the position of every focal point is the inverse of its correspondent radiant point. It is obvious, then, that the left half of the retina corresponds with the right half of the field of view, and the right half of the former to the left half of the latter; and so also the upper half of the former corresponds to the lower half of the latter, and the lower half of the former to the upper half of the latter.

There are some peculiarities of vision which we are now prepared to explain.

1. Properties of the Central Spot, and of its Representative in the Visual Field.—We have already stated that there are two spots on the retina where the constituent layers do not all exist. The central spot is destitute of all except the bacillary layer; the blind spot, of all except the fibrous layer.

The central spot (*macula centralis*) is a small depression not more than one thirtieth of an inch in diameter, situated directly in the axis of the eye, or what might be called the south pole of this globe. It differs from other parts of the retina (*a*) by wanting the fibrous and granular layers; therefore the retina is much thinner there, and the spot is consequently pit-shaped, and on this account is often called the *fovea centralis*, or central pit. Of course, the absence of other layers exposes the bacillary layer here to the direct action of light. It differs again (*b*) by the presence of a pale-yellow coloring matter in the retinal substance; hence it is sometimes called *macula lutea*—the yellow spot. It differs, again, (*c*) in a finer organization than any other part of the retina. The bacillary layer here consists only of cones, and these are far smaller, and therefore more numerous, than elsewhere; being here, as already seen (page 58), only $\frac{1}{10000}$ of an inch in diameter.

Function of the Central Spot.—Every point on the retina, as already seen, has its correspondent or representative in the field of view. Now what is the representative of the central spot? It is evidently the point, or rather *the line, of sight.* From its position in the axis of the eye, it is evident that on it must fall the image of the object or part of the object looked at, or of all points in the visual line or line of sight. Now, if we look steadily and attentively on any spot on the wall, and, without moving the eyes, observe the gradation of distinctness over the field, we find that the distinctness is most perfect at the point of sight and a very small area about that point, and becomes less and less as we pass outward in any direction toward the margins of the field of view. Standing two feet from the wall, I look at my pen held at arm's length against the wall, and of course see the pen distinctly. Looking still at the same spot, I move the pen to one side eight or ten inches: I now no longer see the hole in the back of the pen. I move it two feet or more to one side: I now no longer see the shape of the pen. I see an elongated object of some kind, but can not recognize it as a pen without turning my eyes and bringing its image on the central spot. Hence, to see distinctly a wide field, as in looking at a landscape or a picture, we unconsciously and rapidly sweep the line of sight over every part, and then gather up the combined impression in the memory.

Now the point of sight with a very small area about it corresponds to the central spot, and the margins of the field of view correspond to the extreme forward margin of the retina. Therefore the organization of the retina for distinct perception is most perfect in the central spot, and becomes gradually less and less perfect as we pass toward the anterior margin, where its perception is so imperfect that we can not tell exactly where the field of view ends, except where it is limited by some portion of the face.

Now what is the use of this arrangement? Why would it not be much better to see equally distinctly over all portions of the field of view? I believe that the existence of the central spot is necessary to fixed, thoughtful attention, and this again in its turn is necessary for the development of the higher faculties of the mind. In passing down the animal scale, the central spot is quickly lost. It exists only in man and the higher monkeys. In the lower animals, it is necessary for safety that they should see well over a very wide field. In man, on the contrary, it is much more necessary that he should be able to fix undivided attention on the thing looked at. This would obviously be impossible if other things were seen with equal distinctness. This subject is more fully treated in the final chapter of this work.

It is evident, then, that distinctness of vision is a product of two factors, viz.: 1st, an optical apparatus for distinct image on the retina; and 2d, a retinal organization for distinct perception of the image thus formed. These two factors are perfectly independent of each other. If I hold up my pen before my eye, but very near, and then look at the sky, the outlines of the pen are blurred because the retinal image is so, but my perception is perfect. *I can observe with great accuracy the exact degree of indistinctness.* But if I hold the pen far to one side, say 90°, from the line of sight—on the extreme verge of the field of view—it is again indistinct, much more so than before, but from an entirely different cause, viz., *imperfect perception* of the retinal image. In fact, my perception is so imperfect that I can not tell whether the image is perfect or not. Thus there are two forms of indistinctness of vision, viz., indistinctness from imperfect retinal image, and indistinctness from imperfect retinal perception. The former is an effect of the optical instrument, the latter of the organization of the sensitive plate.

It is evident from the above that an elaborate structure of the lens, for making very exact images of objects on the margins of the field of view, would be of no use to man for want of corresponding distinctness of perception in the anterior margins of the retina. Therefore, as already stated on page 37, the peculiar structure of the crystalline, viz., its increasing density to the center, is of use to man only as correcting aberration, and not in conferring the faculty of periscopism. In the lower animals, however, in which periscopism is so important, this structure of the lens subserves both purposes. So far as this property is concerned, therefore, the structure in man may be regarded as having outlived its use.

Minimum Visibile.—Is there a limit to the smallness of a visible point? This question has been discussed by metaphysicians. But, as usually understood by them, there is no such thing as a *minimum visibile.* There is no point so small that it can not be seen if there be light enough. For example: a fixed star may be magnified 10 diameters, 100 diameters, 1,000 diameters, 5,000 diameters, and still it is to us a mathematical point without dimensions. How much more, therefore, is it without dimensions to the naked eye! And yet it is perfectly visible. The only sense in which science recognizes a minimum visibile is the *smallest space or object which can be seen as a surface or as a magnitude*—the smallest distance within which two points or two lines may approach each other and yet be perceived as two points or two lines. In this sense it is a legitimate inquiry; for there is here a real limit, which depends on the perfection of the eye as an instrument and the fineness of the organization of the retina.

We can best make this point clear by showing a similar property, but far less perfect, in the lower sense of touch. There is also a *minimum tactile.*

Experiment.—Take a pair of dividers; stick on each point a mustard-seed shot, so that the impression on the skin shall not be too pungent. Now try, on another person whose eyes are shut, the least distance apart at which two distinct impressions can be perceived. It will be found that, on the middle of the back, it is about 3 inches; on the arm or back of the hand, it is about ½ to ¾ inch; on the palm, about ¼ inch; on the finger-tips, about $\frac{1}{12}$ or $\frac{1}{16}$ inch; and on the tip of the tongue, about $\frac{1}{20}$ inch, or less.

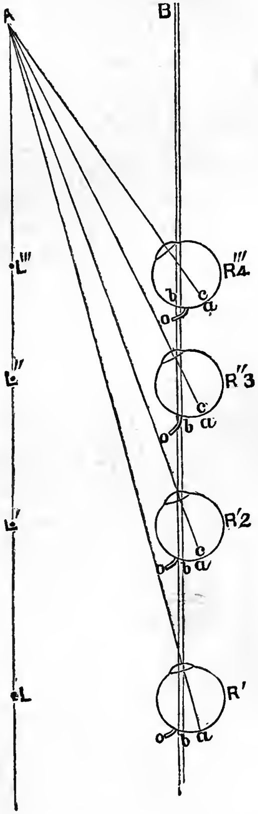
Now, sight is a very refined tact, and the retina is specially organized for an extreme minimum tactile. There is no doubt that the size of the cones of the central spot determines the minimum visibile. If the images of two points fall on the same retinal cone, they will make but one impression, and therefore be seen as one; but if they are far enough apart to impress two cones, then they will be seen as two points. So also of an object: if its image on the retina be sufficient to cover two or more cones of the central spot, then it will be seen as a magnitude. Taking the diameter of central-spot cones to be $\frac{1}{7000}$ (which is the diameter given by some), the smallest distance between two points which ought to be visible at five inches distance is $\frac{1}{1000}$ of an inch. This is found to be about the fact in good eyes.

2. **Blind Spot.**—This is the spot where the optic nerve enters the ball of the eye. Objects whose images fall on this spot are wholly *invisible.* It is for this reason that the point of entrance is always placed out of the axis, about $\frac{1}{6}$ inch on the nasal side. For, if it were in the axis, of course the image of the object we looked at would fall on this spot, and the object would consequently disappear from view. The structural cause of the blindness of this spot we have already explained on page 59. It is the absence of the bacillary layer. The existence of the blind spot may be easily proved by experiments which any one can repeat.

Experiment 1.—Make two conspicuous marks, *A* and *B*, a few inches apart. Then shut the left eye, and

while looking steadily with the right eye at the left object, *A*, bring the paper gradually nearer and nearer: at a certain point of approach *B* will disappear utterly. Continue to bring the paper nearer, still looking steadily at *A*: at a certain nearer point *B* will reappear. The explanation is as follows: At first, when the paper is at considerable distance, say 18 inches, the image of *A* is, of course, on the central spot, for the axis of the eye is directed toward this point; but the image of *B* falls a little to the internal or nasal side of the central spot, viz., between the central spot and the blind spot. Now, as the paper comes nearer, the eye turns more and more in order to regard *A*, the image of *B* travels slowly over the retina noseward until it reaches the blind spot, and the object disappears. As the paper still approaches, the image of *B* continues to travel in the same direction until it crosses over the blind spot to the other side, when the object immediately reappears.

Fig. 25.



The accompanying diagram, Fig. 25, illustrates this phenomenon. Let *A* and *B* represent the two objects, and *R* and *L* the positions of the right and left eyes respectively. The right is drawn, but the left, being shut, is not drawn, but only its position indicated by the dot. The central spot is represented by *c*, in the axis *A c*, and the blind spot by *o*, where the optic nerve enters. It is obvious that the image *a* of the object *A* will be always on *c*, and the place of the image of *B* is on the intersection *b* of the line *B b* with the retina. Now, as the eye approaches the objects *A* and *B*, it is seen that the image *b* of *B* travels toward the blind spot, *o*. At the second position of the eye, *R′*, it has not reached it. At the third position, *R″*, it is upon it.

At the fourth position, R''', it has already crossed over and is now on the other side. At the third position, R'', the object *B* disappears from view.

The distance at which the disappearance takes place will, of course, depend on the distance between the objects *A* and *B*. If these are 3 inches apart, then the disappearance on approach from a greater distance takes place at about 1 foot, and the reappearance at about 10 inches. If the objects be 1 foot apart, then the disappearance takes place at 48 inches, and the reappearance at 38 inches.

Experiment 2.—Place a small piece of money on the table. Shutting the left eye, look steadily with the right at a spot on the table a little to the left of the piece, and move the piece slowly to the right while the point of sight remains fixed; or else, the piece of money remaining stationary, move the point of sight slowly to the left. At a certain distance from the point of sight the piece will disappear from view. Beyond this distance it will reappear.

Experiment 3.—The experiment may be varied in many ways. If, when the object *B* has disappeared from view in the previous experiments, we open the left eye and shut the right, and look across the nose at the object *B*, then *A* will disappear. Thus we may make them disappear alternately. If, finally, we squint or cross the eyes in such wise that the right eye shall look at the left object *A*, and the left eye at the right object *B* (the two, *A* and *B*, had best be similar in this case), then *B* will fall on the blind spot of the right eye and *A* on the blind spot of the left eye, and they will both disappear; but a combined image of *A* and *B* on the central spots of the two eyes will be seen in the middle. This, however, is a phenomenon of binocular vision, and will be explained farther on (see page 107).

Experiment 4.—Any object, if not too large, may be made to disappear by causing its image to fall on the blind spot. For example: From where I now sit writing the door is distant about 10 feet. I shut my left eye and look at the door-knob. I now slowly remove the point of sight and make it travel to the left, but at the same level; when it reaches about 3 feet to the left, the door-knob disappears; when it reaches 4 feet, it reappears. Precisely in the same way a bright star or planet, like Venus or Jupiter, or even the moon, may be made to disappear completely from sight.

Size of the Blind Spot.—As every point in the retina has its representative in the visual field, it is evident that the size of the invisible spot is determined by the size of the blind retinal spot. We may, therefore, measure the latter by the former. I have made many experiments to determine the size of the invisible spot. At the distance of 3½ feet (42 inches) I find the invisible spot 12 inches from the point of sight, and 3½ inches in diameter; i. e., a circle of 3½ inches will entirely disappear at that distance. Taking the nodal point of the lenses or the point of ray-crossing at ⅔ of an inch in front of the retina (it is a very little less), an invisible spot of 3½ inches at a distance of 3½ feet would require a blind retinal spot of a little more than $\frac{1}{20}$ inch in diameter. At 36 feet distance the invisible area would be 3 feet; it would cover a man sitting on the ground. At 100 yards distance the invisible area would cover a circle of 8 feet diameter. In a word, the angular diameter of the invisible spot is a little more than 4½°. Helmholtz makes it a little larger than this.

Representative in the Visual Field of the Blind Spot.—Since every condition of the retina has its visible representative in the field of view, it may be asked, "If there be a blind spot, why do we not see it, when we look at a white wall or bright sky, as a black spot, or a dusky or dim spot, or a peculiar spot of some kind?" I answer: 1. With both eyes open there are, of course, two fields of view partly overlapping each other. Now the invisible spots in these two fields do not correspond, and therefore objects in the invisible spot of one eye are seen perfectly by the other eye, and hence there is no invisible area for the binocular observer. But it will be objected that even with one eye we see no peculiar spot on a white wall. I therefore add: 2. That we see distinctly only a very small area about the point of sight, and distinctness decreases rapidly in going from this point in any direction. Therefore the correspondent or representative in the field of view may well be overlooked, unless it be conspicuous, i. e., strongly differentiated from the rest of the general field. 3. But if this were all, close observation would certainly detect it. The true reason is very different, and the explanation is to be sought in an entirely different direction. Writers on this subject have expected to find a visible representative, and have sought diligently but in vain for it. But the fact is, they ought not to have expected to find it. The expectation is an evidence of confusion of thought—of confounding *blackness* or *darkness* with absence of *visual* activity. Blackness or darkness is itself but the outward projection of the unimpressed state of the bacillary layer; but there is no bacillary layer here. We might as well expect to see a dark spot with our fingers as in the representative of the blind spot. A black spot, or a dark spot, or a *visible* spot of any kind, is not the representative in space of a blind or *insensitive* retinal spot. The true representative of a blind spot is simply an *invisible spot*, or, in other words, a *spot in which objects are not seen.* If we could differentiate it in any way, it would be *visible*, which it is not. As it can not be differentiated in any way, the *mind* seems to extend the general ground color of the neighboring field of view over it. This is, however, a psychological rather than a visual phenomenon. It is for a similar reason that it is impossible to see any limit to the field of view, except where it is limited by the parts of the face, as nose, brows, etc. There is a certain limit horizontally outward where vision ceases, but it is impossible to detect any line of demarkation between the visible and the invisible.

3. Erect Vision.—Retinal images are all inverted. External images or signs of objects are outward projections of retinal images. How, then, with inverted retinal images, do we see objects in their right position, i. e., *erect?* This question has puzzled metaphysicians, and many answers characteristic of this class of philosophers have been given. The true scientific answer is found in what is called the "*law of visible direction.*" This law may be thus stated: *When the rays from any radiant strike the retina, the impression is referred back along the ray-line* (*central ray of the pencil*) *into space, and therefore to its proper place.* For example: The rays from a star (which is a mere radiant point) on the extreme verge of the field of view to the *right* enter the eye and strike the retina on its extreme anterior *left* margin; the impression is referred straight back along the ray-line, and therefore seen in its proper place on the right. A star on the left sends its rays into the eye and strikes the right side of the retina, and the

N.B

impression is referred back along the ray-line to its appropriate place on the left. So also points or stars above the horizon in front impress the lower portion of the retina, and the impression is referred back at right angles, or nearly at right angles, to the impressed surface, and therefore upward; and radiants below the horizon, on the ground, impress the upper half of the retina and are referred downward.

Comparison with Other Senses.—There is nothing absolutely peculiar in this; but only a general property of sense refined to the last degree in the case of sight, owing to the peculiar and exquisite structure of the bacillary layer of the retina. For example: Suppose, standing with our eyes bandaged, any one should with a rod push against our body. We immediately infer the direction of the external rod by the direction of the push. Or another example: Suppose we stood naked in a pond of placid water, with eyes bandaged, and some one on shore agitated the water; the advancing waves would after a while reach us and tap gently upon the sensitive skin. Could we not infer the direction of the distant cause from the direction of the blows? Is it any wonder, then, that when the rays of light crossing one another in the nodal point punch against the interior hollow of the retina, we should infer the direction of the cause by the direction of the punch; i. e., that we should refer each radiant back to its proper place in space?

Thus it is seen that it is in no wise contrary to the general law of the senses, that we should refer single radiants, like stars, back to their proper place in space and see them there. But objects are nothing else than millions of radiants, each with its own correspondent focal point in the retinal image. Each focal impression is referred back to its correspondent radiant, and thus the external image is reconstructed in space in its true position, or is reinverted in the act of projection.

Law of Visible Direction.—After these illustrations and explanations we return to the law, and restate it thus: Every impression on the retina reaching it by a ray-line passing through the nodal point *is referred back along the same ray-line to its true place in space.* Thus, for every *radiant* point in the object there is a correspondent *focal* point in the retinal image; and every focal point is referred back along its ray-line to its own radiant, and thus the external image (object) is reconstructed in its proper position. Or it may be otherwise expressed thus: Space in front of us is under all circumstances the outward projection of retinal states. With the eyes open, the field of *view* is the outward projection of the active or *stimulated* state of the retina; with the eyes shut, the field of *darkness* is the outward projection of the *unstimulated* or passive state of the retina. Thus the *internal retinal concave* with all its states is projected outward, and becomes the *external spatial concave,* and the two correspond, point for point. Now the lines connecting the corresponding points, external and internal, cross each other at the nodal point, and impressions reach the retina and are referred back into space along these lines; or, in other words, these corresponding points, spatial and retinal, exchange with each other by impression and external projection. This would give the true position of all objects and of all radiants, and therefore completely explains erect vision with inverted retinal image.

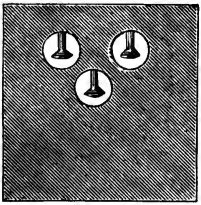
We see, then, that the sense of sight is not exceptional in this property of direction-reference. But what is exceptional is the marvelous perfection of this property—the mathematical accuracy of its perception of direction. This is the result partly of the remarkable structure of the bacillary layer. Every rod and cone has its own correspondent in space, and the extreme minuteness and therefore number of separably discernible points in space are measured by the minuteness and therefore number of the rods and cones of the bacillary layer. Also the perpendicular direction of the rods and cones to the retinal concave is probably related to the direction of projection of impressions into space, and therefore to the accuracy of the perception of direction.

Illustrations of the Law of Direction.—There are many interesting phenomena explained by this law, which thus become illustrations of the law.

Since inverted *images* on the retina are reinverted in projection and seen erect, it is evident that *shadows* of objects thrown on the retina, not being inverted, ought to become inverted in outward projection, and therefore seen in this position in space. This is beautifully shown in the following experiment.

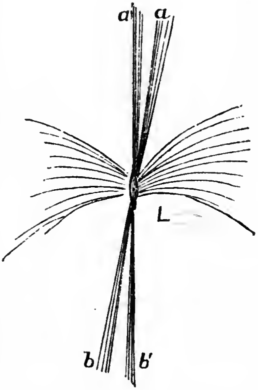
Experiment 1.—Make a pin-hole in a card, and, holding the card at four or five inches distance against the sky before the right eye with the left eye shut, bring the pin-head very near to the open eye, so that it touches the lashes, and in the line of sight: a perfect *inverted* image of the pin-head will be seen in the pin-hole. If, instead of one, we make several pin-holes, an inverted image of the pin-head will be seen *in each pin-hole*, as shown in Fig. 26. The explanation is as follows: If the pin were farther away, say six inches or

FIG. 26.



more, then light from the pin would be brought to focal points and produce an image on the retina; and this image, being inverted, would by projection be reinverted, and the pin would be seen in its real position. In the above experiment, however, the pin is much too near the retina to form an image. But nearness to the retinal screen, though unfavorable for producing an image, is most favorable for *casting a sharp shadow;* and while retinal images are inverted, retinal shadows are erect. The light streaming through the pin-hole into the eye casts an erect shadow of the pin-head on the retina. This shadow is projected outward into space, and by the law of direction is inverted in the act of projection, and therefore seen in this position in the pin-hole. It is further proved to be the outward projection of a retinal shadow by the fact that, by multiplying the pin-holes or sources of light, we multiply the shadows, precisely as shadows of an object in a room are multiplied by multiplying the lights in the room.*

FIG. 27.



Experiment 2.—If we look at a strong light, such as the flame of a candle or lamp, or a gas-flame, at some distance and at night, and thus bring the lids somewhat near together, we observe long rays streaming from the light in many directions, but chiefly upward and downward. Fig. 27 gives the phenomenon as I see it. The explanation is as follows: In bringing the lids near

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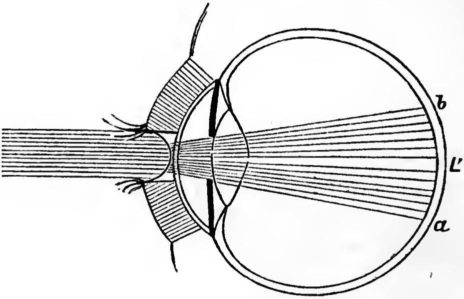
* This phenomenon was first explained by the author in 1871. See "Philosophical Magazine," vol. lxi, p. 266.

together, the moisture which suffuses the eye forms a concave lens, as in Fig. 28 (hence the phenomenon is much more conspicuous if there be considerable moisture in the eyes). This watery lens will be saddle-shaped—i. e., concave vertically and convex horizontally. Now the rays from the light (*L*, Fig. 27) which penetrate the center of the pupil will pass directly on without refraction except what is normal, and make its image (Fig. 28, *L′*) on the central spot. But the rays which strike the curved surface of the watery lens will be bent upward to *b* and downward to *a*. Thus the light, instead of being brought to a focal point, is brought to a long focal line, *b a*, on the retina, with the image of the light in the middle at *L′*. The upper portion of this line *b L′* will be projected outward and downward, and form the downward streamers of Fig. 27; while the lower portion of the retinal impression *a L′* will be projected outward and upward, and form the upward streamers of Fig. 27. To prove this, while the streamers are conspicuous, with the finger lift up the upper lid: immediately the lower streamers disappear; now press down the lower lid: immediately the upper streamers

Fig. 28.



disappear. Also, by shutting alternately one eye and the other, it will be seen that *a b* (Fig. 27) belongs to the right eye and *a′ b′* to the left.

The much lighter diverging side-rays are more difficult to account for. I attribute them to the slight crinkling of the mucus covering the cornea in bringing the lids together.

PART II.

BINOCULAR VISION.

CHAPTER I.

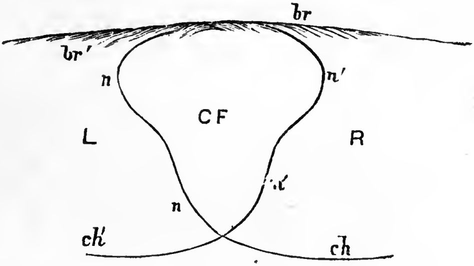
SINGLE AND DOUBLE IMAGES.

The Two Eyes a Single Instrument.—We have thus far treated only of the phenomena of monocular vision; and all that we have said might still apply, almost word for word, if, like the Cyclops Polyphemus, we had but one eye in the middle of the forehead. But we have two eyes; and these are not to be considered as mere duplicates, so that if we lose one we still have another. On the contrary, the two eyes act together as one instrument; and there are many visual phenomena, and many judgments based upon these phenomena, which result entirely from the use of two eyes as one instrument. These form the subject matter of *Binocular Vision.* It must be clearly understood that the distinctive phenomena of binocular vision require two eyes acting as one. We might have two eyes, or even, like Argus, a hundred eyes, and yet not enjoy the advantages of binocular vision; for each eye might see independently. This would still be monocular vision.

The phenomena of binocular vision are far less purely physical than those of monocular vision. They are also far more obscure, illusory, and difficult of analysis, because far more subjective and far more closely allied to psychical phenomena. From early childhood I have amused myself with experiments in this field, and have thus acquired an unusual voluntary power over the movements of the eyes, and a still more unusual power of analysis of visual phenomena. This has always therefore been a favorite field for me; but with a little practice any one may acquire similar power and enjoy a similar pleasure.

Binocular Field.—We have said that the field of view is naught else than an outward projection of retinal states. With the eyes open and the retina in an active or stimulated condition, we call it the *field of view;* with the eyes shut and the retina in a comparatively passive or unstimulated condition, we call it the *field of darkness.* In either case, every variation in the state of different parts of the retina, whether by shadows or by images, or by its own internal changes or unstimulated activity, is faithfully represented in external space by spectra, external images, etc. But we have *two* eyes, and therefore two retinæ, and therefore also two fields of view, the external projections of

Fig. 29.



the two retinæ. These two fields of view partly overlap each other, so as to form a common or binocular field. Fig. 29 represents roughly the form of these fields in my own case. The right field, *R*, is bounded by the line of the nose *n n* on the left, the brows *br* above, and the cheek *ch* below. The field of the left eye, *L*, is bounded similarly on the right by the nose *n′ n′*, the brow *br′*, and the cheek *ch′*. Between the lines of the nose, *n n*, *n′ n′*, is the rounded triangular space *C F*, which is the common or binocular field. This common field is the only part seen by both eyes. The two fields are left vacant on the extreme right and left, because, projected on a plane surface, they are unlimited in these directions. This is the necessary result of the fact that in a horizontal direction the field of view of both eyes is more than 180°.

Now, there being two retinæ, there are of course two retinal images of every external object; and since retinal images are projected outward into space as external images, we must have *two external images* of every object. But we see objects only by these external images. Why, then, with two retinal images—ay, and two external images—for every object, do we not see all objects *double?* I answer: *We do indeed see all objects double, except under certain conditions.*

Double Images.—This phenomenon of double images of all objects, except under certain special conditions, is so fundamental in binocular vision, and yet so commonly overlooked by even the most intelligent persons unaccustomed to analyze their visual impressions, that it becomes absolutely necessary first of all to prove it by detailing many experiments, which every one may repeat for himself.

Experiment 1.—Holding up the finger before the eyes, look, not at the finger, but at the wall or the ceiling or the sky. Two transparent images of the finger will be seen, the left one belonging to the right eye and the right one to the left eye. We easily prove this by shutting first one and then the other eye, and observing which image disappears. The images are *transparent*, or shadowy, because they do not conceal anything. The place covered by the right-eye image is seen by the left eye, and the place covered by the left-eye image is seen by the right eye. If we alternately shut one eye and then the other, the wide difference between these places is at once evident. Often there is an alternation in the distinctness of these shadowy images—first one and then the other fading away, and almost disappearing from view.

Experiment 2.—Point with the forefinger at some distant object, looking with both eyes open at the object, not the finger. Two fingers will be seen, one of them pointing at the object and the other far out of range, usually to the right.

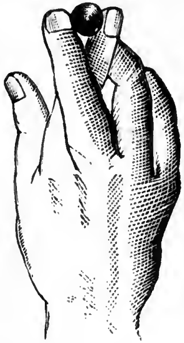
Most persons find some difficulty at first in being conscious of perceiving two images. The reason is, they do not easily separate what they know from what they see. They *know* there is but one finger, and therefore they think they *see* but one. The best plan is to shut alternately one eye and then the other, and observe the places of projection of the finger against the wall; and then, opening both eyes, shadowy images at both these places will be seen. I have found some trouble in convincing a few persons, and have found one single person whom I could not convince, that there were two images. To such a person all that I am about to say on binocular vision will be utterly unintelligible. The whole cause of the difficulty in perceiving at once double images is, that we habitually neglect one image unless attention is specially drawn to it. I have found that nearly all persons neglect the right-hand image—i. e., the image belonging to the left eye. In other words, they are *right-eyed* as well as right-handed. I have also tried the same experiment on several left-handed persons, and have found that these neglected the left image—i. e., the image belonging to the right eye. In other words, they were *left-eyed* as well as left-handed. There is no doubt that dextrality affects the whole side of the body, and is the result of greater activity of the left cerebral hemisphere. People are right-handed because they are *left-brained.*

I pause a moment in order to draw attention here to the uncertainty of some so-called *facts of consciousness.* I have often labored to convince a person, unaccustomed to analyze his visual impressions, of the existence of double images in his own case. He would appeal with confidence, perhaps with some heat, to his consciousness against my reason; and yet he would finally admit that I was right and he was wrong. So-called facts of consciousness must be scrutinized and analyzed, and subjected to the crucible of reason, as well as other supposed facts, before they should be received.

Experiment 3.—Place the two forefingers, one before the other, in the middle plane of the head (i. e., the vertical plane through the nose, and dividing the head into two symmetrical halves), and separated by a considerable distance—say one 8 inches and the other 18 to 20 inches from the eyes. Now, if we look at the farther finger, it will be of course seen single, but the nearer one is double; if we look at the nearer finger, this will be seen single, but the farther one is now double; but it is impossible to see both of them as single objects at the same time. By alternately shutting one eye and then the other, we can observe in either case which of the double images disappears. Thus we will learn that when we look at the farther finger, the nearer one is so doubled that the left image belongs to the right eye and the right image to the left eye; while, on the contrary, when we look at the nearer finger, the farther one is so doubled that the right image belongs to the right eye and the left image to the left eye. In the former case the images are said to be *heteronymous*, i. e., of different name, and in the latter case they are said to be *homonymous*, i. e., of the same name, as the eye.

Analogues of Double Images in Other Senses.—Whenever it was possible, we have traced the analogy of visual phenomena in other senses. Is there any analogue of double vision to be found in other senses? There is, as may be shown by the following experiment: If we cross the middle finger over the forefinger until the points are well separated, and then roll a small round body like a child's marble about on the table between the points of the crossed fingers, we will distinctly perceive two marbles. The points of the fingers touched by the marble are non-corresponding. (Fig. 30.)

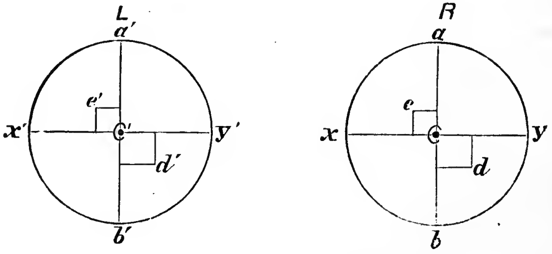
FIG. 30.



Single Vision.—Therefore it is evident that when we look directly at anything we see it single, but that all things nearer or beyond the point of sight are seen double. We then come back to our previous proposition, that we always see things double except under certain conditions. What, then, are the conditions of single vision? I answer: *We see a thing single when the two images of that thing are projected outward to the same spot in space, and are therefore superposed and coincide.* Under all other conditions we see them double. Again, the two external images of an object are thrown to the same spot, and thus superposed and seen single, when the two retinal images of that object fall on what are called *corresponding points* (or sometimes identical points) *of the two retinæ.* If they do not fall on corresponding points of the two retinæ, then the external images are thrown to different places in space, and therefore seen double. We must now explain the position of corresponding points of the two retinæ.

Corresponding Points.—The retinæ, as already seen, are two deeply concave or cup-shaped expansions of the optic nerve. If *R* and *L*, Fig. 31, represent a projection of these two retinal cups, then the black spots *C C′*, in the centers of the bottom, will represent the position of the central spots. If now we draw vertical lines (vertical meridians), *a b*, *a′ b′*, through the central spots, so as to divide the retinæ into two equal halves, then the right halves would correspond point for point, and

FIG. 31.

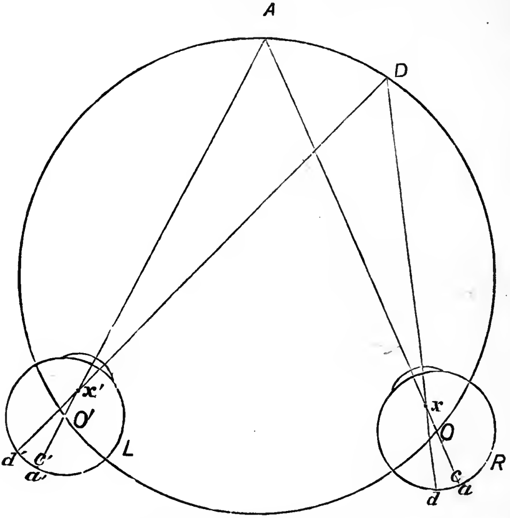


the left halves would correspond point for point; i. e., the internal or nasal half of one retina corresponds with the external or temporal half of the other, and *vice versa.* Or, more accurately, if the concave retinæ be covered with a system of rectangular spherical coördinates, like the lines of latitude and longitude of a globe, $a\ b$ and $x\ y$ being the meridian and equator, then points of similar longitude and latitude in the two retinæ, as $d\ d'$, $e\ e'$, are corresponding. Or, still better, suppose the two eyes or the two retinæ to be placed one upon the other, so that they coincide throughout like geometric solids; then the coincident points are also corresponding points. Of course, the central spots will be corresponding points; also points on the vertical meridians, $a\ b$, $a'\ b'$, at equal distances from the central spots, will be corresponding; also points similarly situated in similar quadrants, as $d\ d'$, $e\ e'$, etc. It is probable that the definition just given is not mathematically exact for some eyes. It is probable that in some eyes the apparent vertical meridian which divides the retinæ into corresponding halves is not perfectly vertical, but slightly inclined outward at the top. This would affect all the meridians slightly; but the effect is very small, and I do not find it so in my eyes. We shall discuss this point again (page 146).

Law of Corresponding Points.—After this explanation we reënunciate the law of corresponding points: *Objects are seen single when their retinal images fall on corresponding points.* If they do not fall on corresponding points, their external images are thrown to different places in space, and therefore are seen double.

Thus we see that the term "corresponding points" is used in two senses, which must be kept distinct in the mind of the reader. Every rod and cone in each retina has its correspondent in external space, and these exchange with each other by impression and projection. Also every rod or cone of each retina has its correspondent in a rod or cone in the other retina. Now the law of corresponding points, with which we are now dealing, states that the two *external or spatial correspondents* of two retinal corresponding points *always coincide with each other*. In order to distinguish these two kinds of corresponding points from each other, the latter—i. e., corresponding points on the two retinæ—are often, and perhaps best, called "identical points," because their external spatial representatives are really *identical*.

Fig. 32.

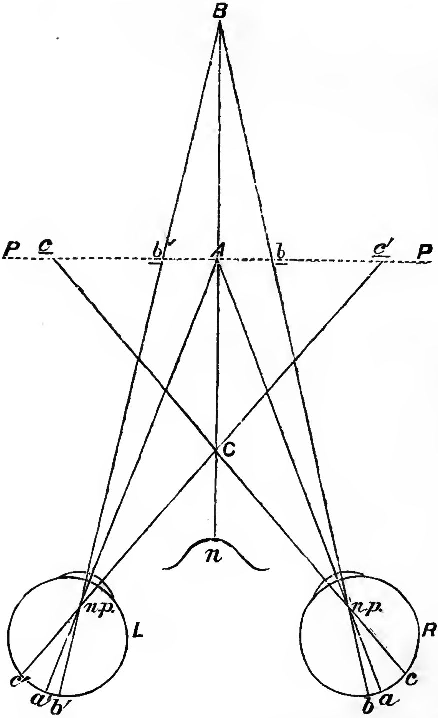


R and L, two eyes; O, center of rotation of ball, or optic center; x, point of crossing of ray-lines—nodal point; A, point of sight; D, some other point in the horoptoric circle $A\ O\ O'$; $c\ c'$, central spots; $a\ a'$, $d\ d'$, actual images of A and D.

We will now apply the law. If we look directly at any small object, it will be seen single, because the two retinal images fall on corresponding or identical points, viz., on the two central spots. In Fig. 32 the two eyes, *R* and *L*, are turned directly on *A*. The image of this object will therefore fall on the central spots *c c′*, and the object will be seen single. Objects at nearly the same distance, as for example *D*, a little to the right or left or a little above or below the point of sight, are also seen single; because the retinal images *d* and *d′* are on correspondent halves—i. e., the internal or nasal half of *R* and the external or temporal half of *L*—and at the same distance from the central spots *c c′*, and therefore on identical points. Objects lying in a horizontal circle passing through the point of sight and the centers of the eyes, *O O′*, are usually supposed to be seen single. This is nearly true, except when the point of sight is very near. This circle has been called the *horopteric circle* of Müller.

Objects, as already said, beyond or nearer than the point of sight, are always seen double. The reason is, that their retinal images always fall on non-corresponding points. This is shown in the diagram Fig. 33. While the two eyes, *R* and *L*, are fixed upon *A*, this object will be seen single, for its images, *a* and *a′*, fall upon the central spots. But if, while still looking at *A*, we observe *B* and *C*, we shall see that both are double. The reason is, that the images of *B*, viz., *b b′*, fall upon the two nasal or internal halves of the retinæ, which are non-corresponding; while the images of *C*, viz., *c c′*, fall upon the two external or temporal halves of the retinæ, which are also non-corresponding. If the external double images be all referred to the plane of sight, *P P* (which, however, is not the fact), as is usually represented in diagrams, then the position of the double images will be correctly represented by *c c′*, *b b′*. It is seen at a glance that the images *c c′* of *C* are heteronymous, while the images *b b′* of *B* are homonymous. Generally, all the field of view within the lines of sight, *A a*, *A a′*, belongs to the temporal halves of the retinæ, while all outside of these lines belongs to the nasal halves. Or, again, double images formed by impressions on the two nasal halves of the retinæ are homonymous, while those formed by impressions on the two temporal halves are heteronymous.

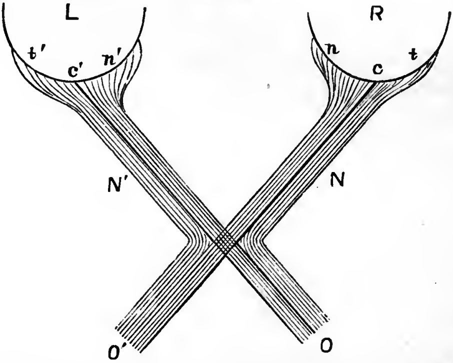
FIG. 33.



Definition of Horopter.—We have seen that the object at the point of sight is seen single; and all objects at the same or nearly the same distance, but a little to the right or left, or above or below, are also either seen single, or else the doubling, if any, is usually imperceptible. On the contrary, all objects farther or nearer than the point of sight are seen double. Now the *surface of single vision*—i. e., the surface passing through the point of sight, all the objects lying in which are seen single—is called the *horopter*. Whether there is such a surface at all, and if there is, what is its form, are questions upon which the acutest observers differ. Some have made it a plane, some a spherical surface. Some, by purely geometrical methods, have given it the most curious forms and properties; while others, by purely experimental methods, have come to the conclusion that it is not a surface at all, but a *line*. We are not now prepared to discuss this question, but shall return and devote to it a special chapter.

Supposed Relation of the Optic Chiasm to the Law of Corresponding Points.—In the optic chiasm, Fig. 20, page 54, there is certainly a partial (but only a partial) crossing of the fibers of the two optic nerves. Many physiologists connect this fact with this remarkable law. There is probably such a connection. But many go farther. They think that some of the fibers of each optic nerve cross over to the other eye, and some do not; and that those which cross over supply the internal or nasal halves, and those which do not cross over supply the temporal halves. Thus, in the diagram Fig. 34, the fibers of the right optic nerve-root *O*, as it comes from the brain, go to supply the temporal half *t* of the right retina, and, by crossing, the nasal half *n'* of the left retina, and these are corresponding halves. So also the fibers of the left optic nerve-root *O′* go to supply the temporal half *t′* of the left and nasal half *n* of the right retina. Still further, they think that the fibers coming from corresponding or identical points, or rods, or cones in the two retinæ are not only thus carried by the same optic root, but finally unite to form one fiber, or at least terminate centrally in one brain-cell, and thus form one single sense-impression. It is almost needless to say that, while this is an interesting speculation, it is nothing more; for the supposed union of fibers from corresponding rods or cones can probably never be either proved or disproved.

FIG. 34.



O O′, optic roots; *N N′*, optic nerves; *R* and *L*, sections of the two eyes; *c c′*, central spots; *n n′*, the nasal halves, and *t t′*, the temporal halves, of the retinæ.

Theories of the Origin of this Law.—The perception of direction and the correspondence of retinal and spatial points are certainly inherent properties of the retina, being connected with its structure. The former—i. e., the perception of *direction*—we have seen, is a general property of sensory nerves, only developed into mathematical accuracy in the case of the optic nerve;

the latter—i. e., the correspondence of retinal and spatial points—is only the expression of this mathematical accuracy of perception of direction; and both are connected with the structure of the bacillary layer. Undoubtedly, then, this property is innate and antecedent to all experience. What the infant learns by experience is not direction, but distance and size of the object. Direction is a primary datum of sense. But the property of *corresponding points* of the two retinæ and of *identical spatial points* in the two fields of view seems to be less absolutely simple and primary. The questions, "Is this property innate, instinctive, antecedent to experience? or is it wholly the result of experience?" have been long and hotly disputed by the profoundest thinkers on this subject. The former view has been held by Müller, Pictet, and others; the latter by Helmholtz, Brücke, Prévost, and Giraud Teulon: the one is called the *nativistic*, the other the *empiristic theory.*

N. B-

We shall not follow the history of this dispute, nor detail the arguments brought forward on each side; for the tendency of modern science, under the guidance of the theory of evolution, is to bring these two opposite views together, and reconcile them by showing that they are both in a degree true, and therefore not wholly inconsistent with each other. The difficulty heretofore has been that anatomists and physiologists have studied man too much apart from other animals, and thus the amount of inherited, innate, instinctive qualities has been greatly underestimated by some and overestimated by others. A new-born chicken, in a few minutes after breaking the egg-shell, will see an object, direct the eyes upon it, walk straight up to it, and seize it. Evidently there is in this case not only a perception of direction, antecedent to all experience, but also some perception of distance, and the wonderful coördination of muscles necessary for standing and walking, and directing the movements of the eyes. A young ruminant animal in a few minutes after birth will stand and walk, and direct its motions by sight. A bird of wild species, hatched in a cage and kept in a cage until it is fully fledged and its muscles are sufficiently developed, if then thrown into the air, will fly away with ease, although the coördination of many muscles in the act of flying is something so marvelous that it could not be learned in a lifetime of trial, unaided by inherited capacity. Inherited powers are still more marvelous in the case of insects.

Manifestly, then, the wealth of capacities in all directions possessed by the individual is partly inherited and partly acquired by individual experience. In animals the inherited, in man the individually acquired, wealth predominates. But all wealth is acquired. Even that inherited is ancestral experience accumulated and transmitted by the law of heredity. Even instinct is "inherited experience." Thus, then, it is evident that the property of corresponding points of the two retinæ, and therefore of identical points in space, is partly inherited and partly acquired by individual experience. It is doubtless wholly the result of experience, but not wholly of *individual* experience.

N.B

Consensual Adjustments.—There are therefore two adjustments of the eye in every voluntary act of sight, viz., *focal* and *axial*. In the former, *each eye* is adjusted by the ciliary muscle to make a perfect image on the retina; in the latter, the *two eyes* are turned by the recti muscles so that their axes shall meet on the point of sight, and the images of the object looked at shall fall on the central spots. The one is an adjustment for *distinct* vision, the other for *single* vision. There is associated with these still a third adjustment, but of far less importance, viz., the *adjustment of the pupil.* The pupil contracts and expands not only as the light is bright or faint, but also as the object is near or far. These three adjustments take place together and without distinct volition for each—i. e., by the one voluntary act of *looking.* They are therefore consensual movements, and usually regarded as indissolubly associated. We shall show hereafter that under certain circumstances they may be dissociated.

The two Fundamental Laws.—There are also two great and fundamental laws by which all visual phenomena are explained, viz., the *law of direction* and the *law of corresponding points.* The one gives the true position of all points in space, and therefore entirely explains the apparent anomaly of erect vision with inverted retinal images; the other gives coincidence of corresponding points in the two fields of view, and therefore entirely explains the second anomaly of single vision with two retinal images. Both may in fact be called laws of corresponding points. The one asserts the correspondence point for point of retinal rods and cones with external space, with ray-lines connecting and crossing in the nodal point; the other asserts a correspondence point for point of the rods and cones of the two retinæ, and the coincidence of their representatives in the two fields of view. From the one law flow all the phenomena of *monocular*, from the other all the phenomena of *binocular* vision.

All the phenomena of binocular vision are explained by the law of corresponding points. But the phenomena are so numerous, so illusory, and so difficult of analysis, that the connection is by no means obvious.

The science of binocular vision consists in tracing this connection, and thus explaining the phenomena. It will be our object, then, to take up all the most important phenomena of binocular vision, and explain them in this way.

CHAPTER II.

SUPERPOSITION OF EXTERNAL IMAGES.

In the movements of one eye, or of the two eyes if they move together equally in the same direction, as in looking to one side or the other, or up or down, objects seem to *stand still*, and the eyes or the point of sight to *sweep over them.* But if we move the eyes in opposite directions, as in converging the optic axes strongly and then allowing them to become again parallel, objects, or rather their external images, seem to sweep like trooping shadows across the field of view; or rather, the fields of view themselves seem to rotate, carrying all their images with them, in a direction contrary to the motion of the eye, and therefore (since the two eyes move in contrary directions) in directions contrary to each other. This phenomenon is not very easily observed, because it is best seen by simple convergence of the eyes on a very near point in space, without any object to direct the convergence, or in trying to look at the root of the nose. Divergence of the eyes may be produced by pressing the fingers in their external corners. In this case also the motion of the images is evident.

Evidently, then, by voluntary motion of the eyeballs in opposite directions, and the consequent motion of the shadowy images in opposite directions, we may (if we observe the images and control the motion of the eyes) cause them, whether they belong to the same object or to different objects, to approach each other and combine successively. Many curious phenomena thus result, which it is necessary to understand before we approach the more complex phenomena, and especially before we can explain the judgments based upon these phenomena.

Combination of the Images of Different Objects.—We have seen that the combination of the two external images of the same object produces single vision. But the external images of different objects may also be combined. Under this head there are several cases.

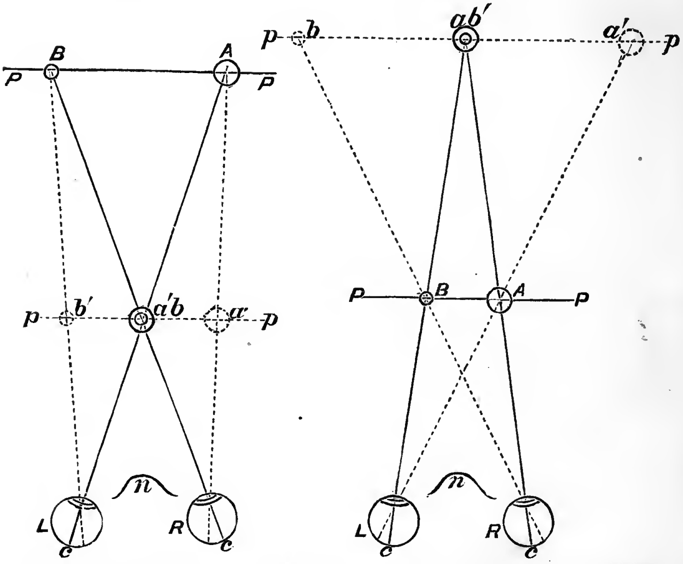
1. **Dissimilar Objects.**—We have seen that when the two images of an object fall on corresponding points of the two retinæ, they are thrown outward as external images to the same point in space, superposed, and united, and therefore the object is seen single. If, instead of the two images of the same object, the images of two different objects fall upon corresponding points, evidently they also will be thrown to the same place in space and superposed. In this case, however, there being two objects, there will be four retinal images, only two of which will fall on corresponding points, and also four external images, only two of which will be superposed. But we may confine our attention to the superposed images, or else we may cut off the others from view, or prevent them from forming.

Experiment 1.—If the left hand and the right forefinger, or any two dissimilar objects, be held up before the eyes, say 8 to 10 inches apart, and then the eyes be converged until the right eye looks exactly toward the left hand and the left eye toward the right forefinger, then evidently the retinal images of these two objects will fall on corresponding points, viz., on the *central spots;* and their corresponding external images ought to be thrown to the same place and superposed. Such is actually the fact. The phenomena as they actually appear are as follows: As the eyes begin to converge, the images of both objects double homonymously, and we see now four images. As the convergence increases, the double images separate more and more, until the left image (belonging to the left eye) of the forefinger and the right image of the hand (this belongs to the right eye) are brought together and superposed, and the forefinger is seen lying in the palm of the hand. Of course, as already explained, there will be two other images—one of the forefinger to the right, and belonging to the right eye, and one of the hand to the left, and belonging to the left eye. By shutting alternately one eye and then the other, these belongings of the several images may be tested.

Experiment 2.—Or, again, the same combination may take place without convergence of the eyes, thus: Hold up the two forefingers before the eyes a foot or so distant, and a little more than two inches apart (it should be equal to the interocular distance), and against a bright background like a white wall or the sky. Now look at the wall or the sky: the two fingers will both double, making four images; but the two middle images will unite to form what seems to be one finger. There will be therefore apparently three images: the middle one (the combined images) is opaque like an object; the other two, uncombined, are transparent like ordinary double images. In this case, as we are gazing beyond the finger, the double images are heteronymous. It is therefore the right-eye image of the right finger (the left of its double images) and the left-eye image of the left finger (the right of its double images) which combine in the middle.

These facts and the conditions under which the combination takes place are illustrated by the accompanying diagrams. In Fig. 35 the right eye, *R*, is directed toward the object *B*, and the left eye, *L*, toward the object *A*. The retinal images of these, falling on the central spots *c c*, are superposed at the point of sight (where the lines of sight intersect) and seen as *a′b*, while two shadowy images, *a* and *b′*, are seen to the right and left. Their position in the plane of sight, and as

Fig. 35. Fig. 36.



In both figures the letters are the same. *R* and *L*, the two eyes; *A* and *B*, two objects; *a′b*, Fig. 35, and *ab′*, Fig. 36, combined images; primed letters, left-eye images; *c c*, central spots of retinæ; *n*, the nose; *P P*, plane of objects; and *p p*, plane of sight.

determined by the law of direction, is given by connecting the points *R A* and *L B*. In Fig. 36 the right eye, *R*, is directed toward the object *A*, and the left eye, *L*, toward the object *B*. The point of sight is therefore beyond, at the meeting of the optic axes or lines of sight. There the combined images, *ab′*, will be seen, while two other uncombined images will be seen at points determined by the law of direction, represented by continuing the lines *R B* and *L A* to the plane of sight. It is evident that in this case the two objects *A* and *B* must not be farther apart than the optic centers (interocular space); otherwise the lines of sight will not meet in a point of sight, and therefore the two images will not combine. Simple inspection of the diagrams will explain the phenomena, if the reader will bear in mind that capitals represent objects and small letters external images; and further, that the primed small letters represent left-eye images, the strong lines *P P* the actual plane of the objects, and the dotted lines *p p* the plane of sight or of the images.

Many persons will not at first succeed in making these experiments, on account of the difficulty which most persons experience in watching double images and controlling the movements of the eyes. To such we would recommend the following method: Let the two objects set up before the eyes in the first experiment be other than parts of the body of the observer—for example, a card and a rod, or two rods. Then, while looking at the table on which the objects lie, hold up the forefinger—or better, a pencil—between the eyes and the objects. The pencil will of course be double. Now, by bringing the pencil nearer or carrying it farther, its double images will separate or close up. Bring the pencil into such a position that its double images shall exactly coincide with the centers of the two objects which you desire to combine. If you now look at the pencil, the ocular convergence will be exactly suitable for combining the objects.

In the cases thus far mentioned there is no illusion: the combined images do not produce the appearance of a *real* object, as in the case of combined images of the same object producing single vision; because, in the first place, the two objects are *dissimilar*, and therefore the combination is not perfect; and, in the second place, the illusion is destroyed by the existence of the two other uncombined images. We next try—

2. **Similar Objects.**—If the two objects, the images of which we desire to combine, are exactly similar, then the combined image will be exactly like a natural object. For example:

Experiment 1.—Place two pieces of money of the same kind on the table, being careful that the stamped figures shall be in the same position. Now, looking down upon them, combine as before. Not only will the outlines of the two pieces combine, but the stamped figures in the minutest details, so that the middle combined binocular image will have all the appearance of a real object. This is illustrated by Figs. 37 and 38, in which the position of parts is reversed, because the eyes are supposed to be looking down. In Fig. 37 the two objects (coins), *A* and *B*, are combined by crossing the eyes, and the combined or binocular opaque image will be seen at the point of sight as *a'b*, while monocular shadowy images, *a* and *b'*, will be seen right and left. In Fig. 38 the combination is made by looking beyond the plane of the coins, and the coins in this case must not be more than an interocular space apart. The combined images, like a real opaque object, will be seen at the point of sight *ab′*, and the two shadowy monocular images right and left, as before, only they are now heteronymous.

FIG. 37.

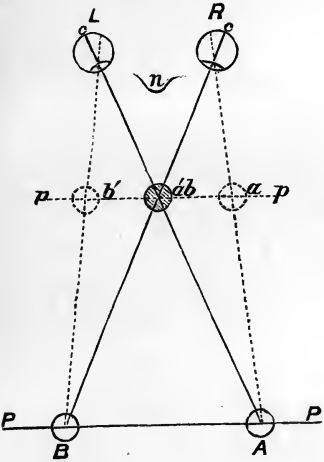
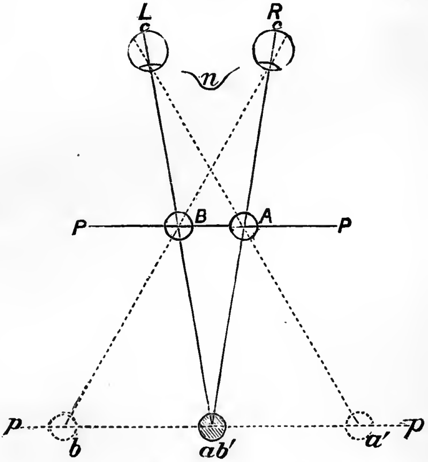


FIG. 38.



In this case, though the combination is perfect, yet the illusion is still not complete, because of the presence of the accompanying monocular images; but the formation of these may be prevented by the use of appropriate screens.

Experiment 2.—If in the first experiment with the money, before combining, we hold two cards, *sc*, *sc′*, Fig. 39, one in either hand and at about half the distance to the table (the best distance is the plane of combination or plane of sight, for then there will be no doubling of the cards), in such position that the card in the right hand, *sc*, will hide the right piece *A* from the right eye but not from the left, and the card in the left hand, *sc′*, will hide the left piece *B* from the left eye but not from the right, and then make the combination by crossing the eyes, the combined binocular opaque image will be formed as before; but the monocular images will not appear, because there will be

FIG. 39.

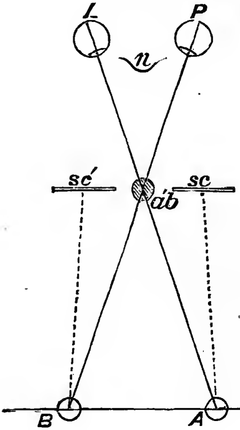
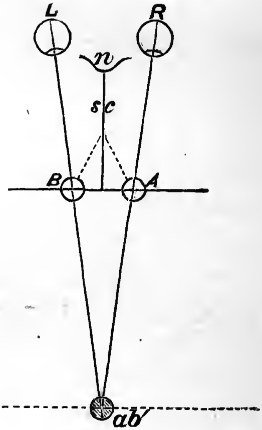


FIG. 40.

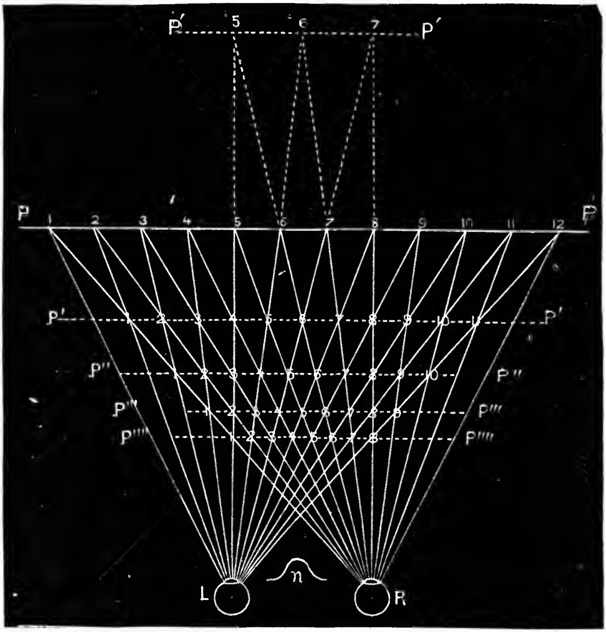


no other retinal image formed except on the central spots. This is represented in Fig. 39. In case we combine beyond the plane of the objects, then a median screen, *sc*, Fig. 40, extending from the root of the nose *n* to the table, midway between the objects, will prevent the formation of the monocular images, as shown.

But in these cases, although the union of the two images is perfect, and although we see nothing but an apparently solid opaque object, even yet the illusion is not absolute; partly because the table is doubled and therefore unreal, and partly because the eye is adjusted to the point of sight, whereas the light comes from the object, which is either nearer as in Fig. 40, or farther off as in Fig. 39, than that point. We will try therefore still another case.

3. Many Similar Objects regularly arranged.—The illusion is most complete when we combine the images of many similar objects regularly arranged over the whole field of view, such as the regular figures of a tessellated pavement or oilcloth, or of a regularly figured carpet of small pattern, or of a papered wall of regular pattern, or the diamond-shaped spaces of a wire grating. In such a case, when by convergence we combine two contiguous figures immediately in front, other contiguous figures all over the plane also combine. In other words, by the motion of the eyes in opposite directions in convergence, the images of the whole plane of the figured surface are slidden by one eye to the left and by the other eye to the right, until combination takes place again over the whole field. When the combination is effected, if we hold the point of sight steady, the combined images of the figures, at first a little blurred, become sharp and clear; and then the whole figured plane comes forward to the point of sight, and appears there as distinctly as a real object, but on a smaller scale in proportion to the less distance. This is represented in Fig. 41, in which the strong line $P\ P$ represents the plane of the regular figures 1, 2, 3, 4, 5, etc. When contiguous figures, 6 and 7, are united by convergence at the point of sight, and seen there, then all other contiguous figures, 1 and 2, 2 and 3, etc., all over the plane, will be similarly united, and the whole plane with all its figures will advance and be distinctly seen at the distance $p'\ p'$. When by stronger convergence alternate figures, 5 and 7, are combined at a nearer point of sight 5 on the plane $p''\ p''$—or (which is the same) when we use the plane $p' \, p'$ first obtained with all its figures as a real object, and again combine contiguous figures—the whole plane advances to $p'' \, p''$, and is seen as a distinct object with a still smaller pattern of figures. Using the plane thus obtained again as an object, and uniting its contiguous figures, the whole plane again advances still nearer, and the figures become still smaller at $p''' \, p'''$. In this manner I have often distinctly seen a regularly figured wall or pavement on six or seven different planes coming nearer and nearer, and becoming smaller and smaller, until the nearest was within 3 inches of the eyes, and the figures

FIG. 41.



in exquisite miniature, and yet the whole so apparently real that it seemed to me I could rap my knuckles against the wall or pavement. When thus looking at the nearest image, by a slight relaxation of convergence we may drop the image and catch it on the next plane, and again drop it to each successive plane, until it falls to its natural place.

If the figures of the pattern are not larger than the distance between the optic centers ($2\frac{1}{2}$ inches), then it is possible also to unite the figures beyond the real plane —i. e., on the plane $P' P'$. In this case the figures will be proportionately enlarged, as shown by the diagram. But it is difficult by this method to make the image clear, the reason for which we shall soon see.

In all cases of illusive images the head ought to be held steady. If it be moved from side to side while gazing at such an image, the image will also move from side to side—in the same direction as the head if the point of sight be nearer than the object, and in the opposite direction if the point of sight be beyond the object. It is necessary too, in all experiments on combination of images, that the interocular line should be exactly parallel with the line joining the objects to be combined; otherwise one image will be higher than the other.

Dissociation of Consensual Adjustments.—We have said above that when the combination in case 3 (and so also in the other cases) is first obtained, the image of the figures is not distinct, but afterward becomes clear and sharp. The reason is this: The voluntary adjustment of the optic axes (axial adjustment) to a nearer distance than the object carries with it, by consensus, the focal adjustment and pupillary contraction for the same distance. But since the lenses are adjusted for a nearer distance than the object, the retinal image will be indistinct. The subsequent clearing of the image, therefore, is the result of a dissociation of the axial and focal adjustments. The optic axes are adjusted for the point of sight or distance of the illusive image, and the lenses are adjusted for the distance of the object. Some persons do not find it easy to make this dissociation, and therefore to make the illusive image perfectly clear. To presbyopic persons it is not difficult, but normal eyes will find some, though not insuperable, difficulty.

Now it becomes an interesting question: When the axial and focal adjustments are thus dissociated, with which one does the pupillary contraction ally itself? I answer, it allies itself with the *focal* adjustment. This may be proved as follows:

Experiment.—While the combination and the formation of the illusive image are taking place, let an assistant standing behind observe the pupil in a small mirror suitably placed in front and a little to one side of one eye. He will see that at first the pupil contracts strongly, associating itself with the axial and focal adjustments to the point of sight; but as soon as the illusive image clears and becomes distinct, he will observe that the pupil has enlarged again.

General Conclusions.—It is evident, therefore, that the combination of the similar images of two different objects may produce the same visual effect as the combination of the two images of the same object. In other words, single vision, or ordinary perception of objects, is by combination of two similar images; and it makes no difference whether the two images belong to the same object or to two different but similar objects. This idea must be clearly apprehended and held fast; otherwise all that follows will be unintelligible.

Again, it is evident that two objects may be seen as one, and, contrariwise, one object may be seen as two images. We see then the absolute necessity, in binocular vision, that we should speak of seeing only *external images*, the *signs of objects.* They are usually—i. e., under ordinary conditions—the true signs, but often untrue, deceptive, illusory signs.

CHAPTER III.

BINOCULAR PERSPECTIVE.

Thus far we have investigated the case of *flat* objects, or of figures or colored spaces *on a plane.* We have shown how the images of these may be combined at pleasure, so as to give the illusory appearance of objects or figures at places and of sizes different from their real places and sizes. We come now to the more complex case of *solid objects of three dimensions*, and of objects situated at *different distances.* This brings us to the important subject of the perception of depth of space so far as this is connected with binocularity; or, in other words, to the subject of *binocular perspective.* We will introduce the subject with some simple experiments.

Experiment 1.—Place one forefinger before the other in the median plane, as in the experiment on page 94. As already seen, when we look at the farther finger, the nearer one is doubled heteronymously; when we look at the nearer finger, the farther one is doubled homonymously. *We can not see them both single at the same time.* The reason is obvious. If we shut one eye, say the left, we see the fingers as in Fig. 42, I; if we shut the right eye, we see them as in Fig. 42, II. Now these two can not be combined, because they are different. When we combine the images of the farther fingers, *a* and *a′*, the nearer, *b* and *b′*, will not have come together yet, and will therefore be heteronymously

Fig. 42.

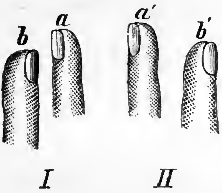
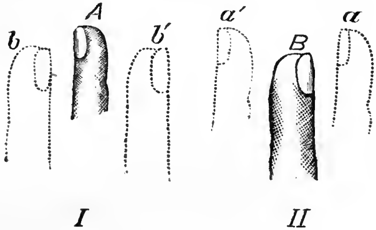
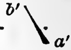
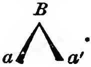
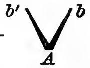
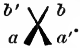
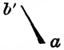


Fig. 43.



double, as in Fig. 43, I; when by greater convergence we combine the images *b* and *b′* of the nearer finger, then the images *a* and *a′* of the farther will have crossed over and become homonymously double, as in Fig. 43, II. As in previous experiments, double images are given in dotted outline, and left-eye images are marked with primed letters, and combined images with capitals.

Now, in this experiment we are distinctly conscious of a *greater* convergence of the optic axes necessary to combine the double images of the nearer finger, and of a *less* convergence to combine the double images of the farther. Thus the eyes range back and forth by greater and less convergence, combining the double images of the one and the other, or transferring the point of sight from one to the other; and thus we acquire a distinct perception of distance between the two. It is literally a rapid process of triangulation, the base-line being the interocular distance.

Experiment 2.—We take a rod about a foot long, and hold it in the median plane a little below the horizontal plane passing through the eyes, so that we can see along its upper edge, the nearer end about six or eight inches from the eyes. If now, shutting the left eye, we observe the projection of the rod against the wall, it will be like this— —*a* being the nearer and *b* the farther end. If we shut the right eye and open the left, the projection will be like this—. These lines are exactly like the retinal images formed by the rod in the right and left eyes respectively, except that these images are inverted. Or, to express it differently, these lines would make images on the right and left retinæ respectively exactly like those made by the rod; they are the facsimiles of the external images of the rod. If we now open both eyes and fix attention on the farther end, then the nearer end will be seen double heteronymously, and the projection will be thus—. If, on the contrary, we look at the nearer end, then this of course will be single, but the farther end will now be double homonymously, and the projection will be thus—. If, finally, we look at the middle point, this point will of course be seen single, but both ends double, the one homonymously, the other heteronymously, and the projection will be thus—. Or, to put it differently, the external images of the two eyes are like these lines— and : if these two be brought together so as to unite the farther ends *b b′*, then by greater convergence the middle points, and then by still greater convergence the nearer ends *a a′*, the three projections above given are obtained; but it is obviously impossible to unite all parts and see single the whole rod at once. Now, if we observe attentively, we find that in looking at the rod the eyes range back and forth by greater or less convergence, uniting successively the different parts, and thus acquire a distinct perception of the difference of distance or depth of space between the nearer and the farther end.

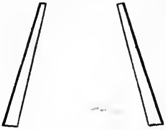
Experiment 3.—We take next a small thin book, and hold it as before six to eight inches distant in the median plane, a little below the horizontal plane of sight, so that the back and the upper edge are visible. If we shut the left eye, we see the back, the upper edge, and the whole right side, thus— . The retinal image formed in the right eye is exactly like this figure, except that it is inverted; this figure makes exactly the same retinal image as the book does in the right eye; it is the facsimile of the external image of the book for the right eye. If we shut the right eye and open the left, we see the back, the upper edge, and the whole left side, thus— . Now, if we open both eyes, we must and do see both these images. If we look beyond the book, the two images are wholly separated, thus—  . If we look at the farther part, we bring these two images together so as to unite the farther part and see it single, but the nearer part or back is double, thus— . If we look at the nearer part or back, then this is seen single, but the farther edge is now double, thus— . But by no effort is it possible to see it single in all parts at the same time, because these dissimilar external images can not be wholly united. The eyes therefore range rapidly back and forth, successively uniting different parts by greater and less convergence, and thus acquire a distinct perception of distance between the back and front, and hence of depth of space.

After these simple illustrations we are now prepared to generalize. It is evident that solid objects as seen by two eyes form different mathematical projections, and therefore form different retinal images in the two eyes, and therefore also different external images. Hence the images of the same object, whether retinal or external, formed by the two eyes, are necessarily dissimilar if the object occupies considerable depth of space. But dissimilar images can not be united wholly: for when by stronger convergence we unite the nearer parts, the farther will be double; and when by less convergence we unite the farther parts, the nearer will be double. Therefore the eyes run rapidly and unconsciously back and forth, uniting successively different parts, and thus acquire the perception of depth of space occupied by the object. But what is true of a single object is true of different objects placed one beyond the other, as the two fingers in experiment 1, page 120. We can not at the same time unite nearer and more distant objects, but the point of sight runs rapidly and unconsciously back and forth, uniting them successively, and thus we acquire a perception of depth of space lying between them. Therefore, *the perception of the third dimension*, viz., *depth or relative distance, whether in a single object or in a scene, is the result of the successive combination of the different parts of the two dissimilar images of the object or the scene:* dissimilar, because taken from different points, viz., the two eyes with the interocular distance between. This fundamental proposition will be slightly modified in our chapter on the theory of binocular perspective. In the mean time it must be clearly conceived and held fast; otherwise all that follows on stereoscopy will be unintelligible.

STEREOSCOPY.

We have already seen (page 96) that in binocular vision we see objects single by a combination of two similar or nearly similar images, and that therefore (page 118) it makes no difference whether the images are those of the same object or of different objects, if the images in the two cases are identical, and if we take care to cut off the monocular images which are formed in the latter case. Hence, if we draw two pictures of a rod in the two positions shown in Fig. 44, and then combine them by converging the eyes, taking care to cut off the monocular images as directed on page 114, Fig. 39, the visual result will be exactly the same as that of an actual rod in the median line; and therefore it will look like such a rod. As in the case of the actual rod, by greater or less convergence of the optic axes we may combine successively different parts; and the eyes therefore seem to run back and forth, and we have a distinct perception of depth of space. To produce the proper effect, the two pictures of Fig. 44 ought to be combined at a distance of not more than six or eight inches

FIG. 44.



So also in the case of the book, page 123. If we exactly reverse the case described there—i. e., if we make two pictures of a book as seen by one eye and the other, and then combine them, cutting off the monocular images—we have the exact appearance of an actual solid book. The only reason why the illusion is not complete is, that there are other kinds of perspective besides the binocular; and in this case especially because there is not the same change of *focal adjustment* necessary for distinct image as in the case of a real object.

Now this is the principle of the stereoscope. The stereoscope is an instrument for facilitating the combination of two such pictures, and at the same time cutting off the uncombined monocular images which would tend to destroy the illusion.

Stereoscopic Pictures.—When we look at an object having considerable depth in space, or at a scene, there is an image of the object or scene formed on each retina. These two images are not exactly alike, because they are taken from different points of view. Now suppose we draw two pictures exactly like these two retinal images, except inverted. Obviously these two pictures will make images on the corresponding retinæ exactly like those made by the original object on the one retina and the other, and therefore will be exactly like this object seen by one eye and then by the other. Now, we have seen the wonderful similarity of the eye to a photographic camera. Suppose, then, instead of drawing the pictures like the two retinal images, we photograph them. Two cameras are placed before an object or a scene with a distance between of two or three feet. They are like two great eyes with large interocular space. The sensitive plate represents the retina, and the pictures the retinal images. The photographic pictures thus taken can not be exactly alike, because taken from different points. *They will differ from each other exactly as the two retinal images of the same object or scene differ*, only certainly in a greater degree. Therefore, if these two photographs be binocularly combined as in the experiments previously given, they ought to and must produce a visual effect exactly like an actual object or scene; for in looking at an object or scene, we are only combining retinal images (or their external representatives) exactly like these pictures, because taken in the same way.

This is substantially the manner in which stereoscopic pictures are taken. It is not always necessary, indeed, to have two cameras; for the pictures, being permanent and not evanescent like retinal images, may be retained and combined at any time. The object or scene is often photographed from one position, and then the camera is moved a little, and the same object or scene is again photographed from the new position. The two slightly dissimilar pictures thus taken are then mounted in such wise that the right-hand picture shall be that taken by the right camera, and the left-hand picture that taken by the left camera. In other words, they are mounted so that the right picture shall be similar (except inverted) to the retinal image of the object or scene in the right eye, and the left picture to the retinal image in the left eye. The marvelous distinctness of the perception of depth of space, and therefore the marvelous resemblance to an actual object or scene, produced by binocular combination of such pictures properly taken and properly mounted, is well known.

It is easy to test whether stereoscopic pictures are properly mounted or not. Select some point or object in the foreground; measure accurately with a pair of dividers the distance between it and the same point or object in the other picture; compare this with the distance between identical points in the extreme background of the two pictures. The distance in the latter case ought to be greater than in the former. This is the proper mounting for viewing pictures in a stereoscope. If they are to be combined with the naked eye, then the reverse mounting is better.

Combination of Stereoscopic Pictures.—Stereoscopic pictures may be easily combined by the use of the stereoscope or with the naked eyes. For inexperienced persons, however, the latter is more difficult and the illusion less complete, unless with special precautions. Nevertheless, it will be best to begin with this method, because the principles involved are thus most easily explained.

Combination with the Naked Eyes.—In combining stereoscopic pictures with the naked eyes, there are two difficulties in the way of obtaining the best results. First, it is evident that such pictures, as usually mounted, were intended to be combined *beyond the plane of the card;* for it is only thus that the object or scene can be seen in natural perspective, and of natural size, and at natural distance. But in thus combining, the eyes are of course looking at a distant object, and consequently parallel or nearly so. The eyes are therefore focally adjusted for a distant object, but the light comes from a very near object, viz., the card-pictures. Hence, although the pictures unite perfectly, the combined image or scene is indistinct. Myopic eyes will not experience this difficulty, and in normal eyes it may be remedied by the use of slightly convex glasses. Such glasses supplement the lenses of the eye, and make clear vision of a near object when the eyes are really looking far away; or, in other words, make a clear image of a near object on the retina of the *unadjusted* eye.

Another difficulty is, that the pictures are usually so mounted that identical points are farther apart than the interocular distance, and therefore, even with the optic axes parallel—i. e., looking at an infinite distance—the pictures do not combine. This difficulty is easily removed by cutting down the inner edges of the two pictures, in order to bring them a little nearer together, so that identical points in the background shall be equal to or a little less than the interocular distance.*

With this explanation we now proceed to give examples of naked-eye combination.

Fig. 45 represents a projection of a skeleton truncated cone made of wire, as seen from two positions a little separated from each other; in other words, as they would be taken by two cameras for a stereoscopic card; or, again, as they would be taken on the retinæ of two eyes looking at such a skeleton truncated cone with the smaller end toward the observer.

FIG. 45.

Experiment.—If we now place a median screen 10 inches or a foot long midway between these two figures,

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* In a subsequent chapter we give the method of determining with accuracy the interocular distance.

A and *B*, and place the nose and middle of forehead against the other edge of the screen, so that the right eye can only see *A* and the left eye *B*—assisting the eye with slightly convex glasses if necessary—and then gaze as it were at a distant object beyond the plane of the picture, the two figures will be seen to approach and finally to unite in one, and *appear as a real skeleton truncated cone* of a considerable height. If we are able to analyze our visual impressions, we shall find further that, when we look steadily at the larger circle or base, the smaller cone or summit is slightly double, and when we look steadily at the smaller circle or summit this becomes single, but now the larger circle or base is double; further, that it requires a greater convergence, as in looking at a nearer object, to unite the smaller circles, and a less convergence, as in looking at a more distant object, to unite the larger circles; and still further, that the lines *a a′* and *b b′* behave exactly like the lines described on page 122, forming a V, an inverted V, or an X, according to the distance of the point of sight; or, in other words, behave exactly like the two images of a rod held in the median plane with one end nearer than the other. In a single word, the phenomena are exactly those produced by looking at an actual skeleton cone made of wires. Thus, as in the case of an actual object, the eyes by greater and less convergence run their point of sight back and forth, uniting different parts, and thus acquire a distinct perception of depth of space between the smaller and larger circles.

The same is true of all pictures constructed on this principle, and all objects or scenes on stereoscopic cards. In these, it will be remembered, identical points in the foreground are always nearer together than identical points in the background; therefore, when the background is united the foreground is double, and *vice versa.* We may represent these facts diagrammatically by Fig. 46, in which *p p* is the plane of the pictures; *ms*, the median screen resting on the root of the nose, *n*; *R* and *L*, the right and left eyes. On the plane of the paper *p p*, *a* and *a′* represent identical points in the foreground, viz., the centers of the small circles in the diagram Fig. 45; and *b* and *b′* identical points in the background (centers of the larger circles in Fig. 45). Now when the eyes are directed toward *b* and *b′*, the two visual lines will pass through these points, and the images of these two points will fall on corresponding points of the retinæ, viz., on the central spots, and will be united and seen single. But where? Manifestly at the point of optic convergence or point of sight *B*. Now when *b* and *b′* fall on corresponding points and are seen single, evidently *a* and *a′* must fall on non-corresponding points, viz., the two temporal portions of the retinæ, and are therefore seen double. When, on the other hand, by greater convergence the optic axes are turned on *a* and *a′*, then the images of these fall on the central spots, and are seen single at the nearer point of sight *A*; but now *b* and *b′* are seen double, because they fall on non-corresponding points, viz., the two nasal halves of the retinæ. Intermediate points between the background and foreground will be seen at intermediate points between *B* and *A*. Thus the point of sight runs back and forth from

FIG. 46.

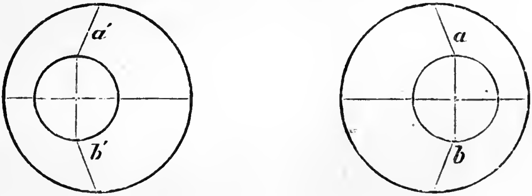
background *B* to foreground *A*, and we acquire a distinct perception of depth of space between these two points.

But, for those at all practiced in binocular experiments, by far the most perfect naked-eye combination is obtained by crossing the eyes; i. e., by combining on the nearer instead of the farther side of the pictures. For this purpose, however, it is necessary that the mounting be reversed; i. e., the right-hand picture must be put on the left side, and the left-hand picture on the right side of the card. By this reversal it is evident that identical points in the background of the two pictures are nearer together than identical points in the foreground.

If, now, holding such a card before us at any convenient distance, say 18 inches or 2 feet, we converge the optic axes so that the right eye shall look across directly toward the left picture, and the left eye toward the right picture, then the two pictures will unite at the point of crossing of the optic axes (point of sight), and will be seen there in exquisite miniature, but with perfect perspective. The effect is really marvelously beautiful. For persons of slightly presbyopic eyes there will be no difficulty in getting the combined image perfectly clear. In normal eyes, as already explained (page 117), there must be dissociation between the axial and focal adjustments before the combined image is perfectly clear. For those who can not make this dissociation it may be necessary to use very slightly concave glasses. Again, if the observer is annoyed by the existence of the monocular uncombined images to the right and left, it will be best to use two side screens, as already explained (page 114), instead of the median screen used in combining beyond the plane of the picture.

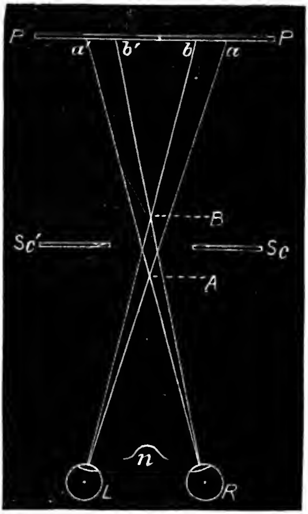
Experiment.—I draw (Fig. 47) two projections of a skeleton truncated cone precisely like those represented on page 129, but reversed. It is seen, for example, that the centers of the small circles are in this case farther apart than the centers of the large circles. If, now, holding these about 18 inches distant, I combine them by crossing the optic axes, the impression of a skeleton truncated cone with the smaller end toward me is as complete as possible. The singleness of the impression at first seems perfect, but by observing attentively the lines *a* and *a′* it will be seen that they unite only in points and not throughout—that they come together as a v, thus—V, or an inverted v—Λ, or an x—X, according to the distance of the point of sight. In other words, when by greater convergence the small circle is single, the larger circle is double; and when by less convergence the larger circle is single, then the smaller circle is double. And thus the eyes run the point of sight back and forth, uniting first the one and then the other, and in this way acquire a clear conception of depth of space between the smaller and larger circles.

Fig. 47.



These facts are illustrated by the diagram Fig. 48, in which, as before, *R* and *L* are the two eyes; *n*, the root of nose; *P P*, the plane of the pictures; *a* and *a′*, identical points of the foreground, and b and b' of the background; and sc and sc', the two side-screens to cut off monocular images. When the eyes are directed toward a and a', these unite and are seen at the point of sight as a single object A. When the eyes by less convergence are directed to b and b', then these are seen single at the point of sight B. The point of sight runs back and forth from A to B, and we thus acquire distinct perception of depth of space between.

FIG. 48.



Of course, any stereoscopic pictures may be combined in this way if we reverse the mounting; and I am quite sure that any one who will try it will be delighted with the beautiful miniature effect and the perfection of the perspective.

Combination by the Use of the Stereoscope.—The stereoscope is an instrument for facilitating binocular combinations beyond the plane of the pictures. By means of lenses also it supplements the lenses of the eyes, and thus makes on the retinæ perfect images of a near object, although the eyes are looking at a distant object, and are therefore unadjusted for a near one. The lenses also enlarge the images, acting like a perspective glass, and thus complete the illusion of a natural scene or object.

It is difficult to convince many persons that there is in the stereoscope any doubling of points in the foreground when the background is regarded, and *vice versa.* But such is really always the fact; and if we do not observe it, it is because we have not carefully analyzed our visual impressions. It is best observed in skeleton diagrams of geometrical figures, such as are commonly used to explain the principles of stereoscopy. In ordinary stereoscopic pictures it is also easily observed in those cases where points in the extreme foreground and background are in the same range; as, for example, when a column far in front is projected against a building. In such a case, when we look at the building the column is distinctly double, and *vice versa.* For myself, I never look at a stereoscopic card, whether in a sterescope or by naked-eye combination, without distinctly observing this doubling. For example: I now combine in a stereoscope the stereoscopic pictures of a skeleton polyhedron. The illusion of a polyhedral space inclosed by white lines is perfect. Now, when I look at the farther inclosing lines I see the nearer ones double, and *vice versa.* Moreover, I perceive that this doubling is absolutely necessary to the stereoscopic effect, for it is exactly like what would take place if I were looking at an actual skeleton polyhedron.

Inverse Perspective.—I have heard a few persons declare that they saw no superiority of a stereoscope over an ordinary enlarging or perspective glass; that they saw just as well while looking through the stereoscope if they shut one eye as with both eyes open. Such persons evidently do not combine properly the two pictures, and they lose a real enjoyment. That the binocular is a real perspective, entirely different from other kinds, may be clearly demonstrated by the phenomena of inverse perspective now about to be described.

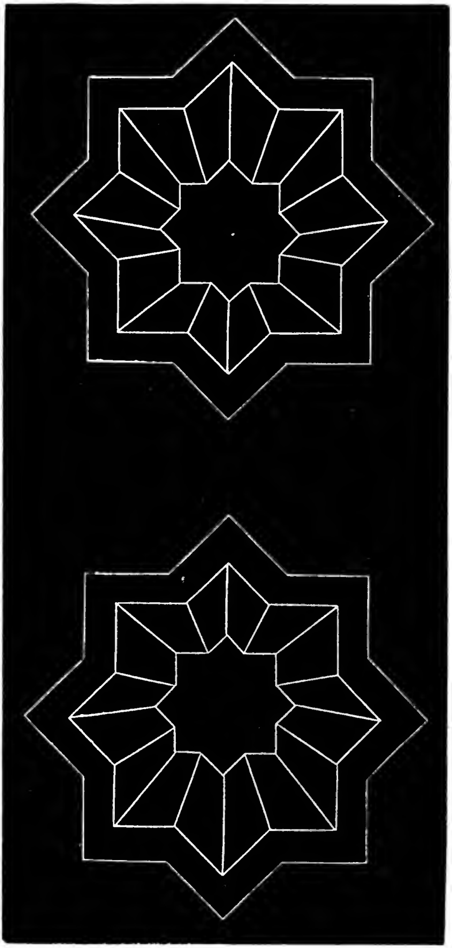


Fig. 49.

If stereoscopic diagrams suitably mounted for viewing in a stereoscope be combined with the naked eye by squinting (crossing the optic axes), as in Fig. 48 (page 134), or if such diagrams properly mounted for

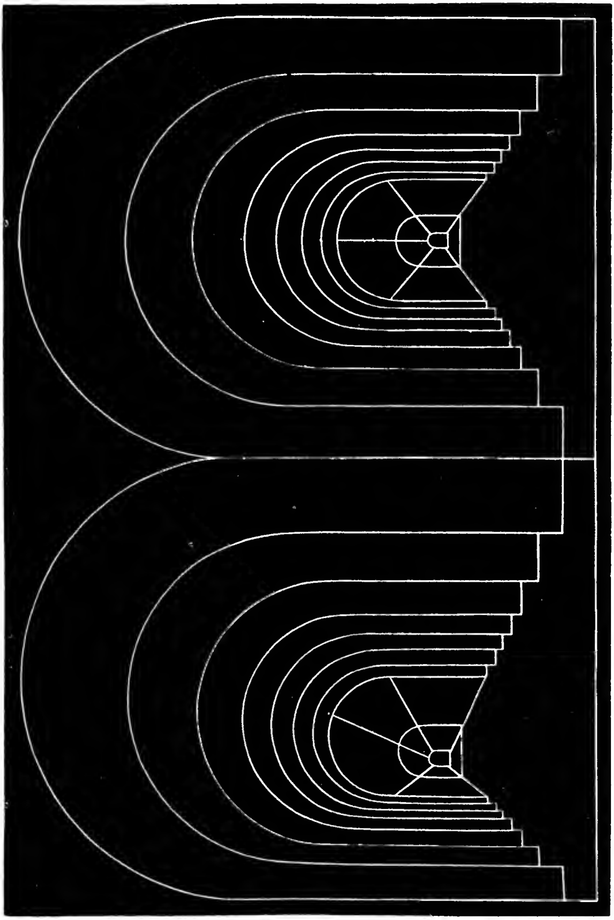


Fig. 50.

combination by squinting be viewed in the stereoscope, the perspective is completely reversed, the background becoming the foreground, and *vice versa*. For example, Fig. 49 represents a stereoscopic card. When the two pictures are combined with a stereoscope, the result is a jelly-mold with the small end toward the observer; but if the same be combined with the naked eye by squinting, we have now beautifully shown the same jelly-mold reversed, and we are looking into the hollow. If there should be other forms of perspective strongly marked in the pictures, these may even be overborne by the inverse binocular perspective. For example, in the stereoscopic picture Fig. 50, representing the interior of a bridgeway, the diminishing size of the arches and the converging lines, even without the stereoscope, at once by mathematical perspective suggest the interior of a long archway. This impression is greatly strengthened by viewing it in the stereoscope; for the binocular perspective and the mathematical perspective strengthen each other, and the illusion is complete. But if we combine these with the naked eyes by squinting, we see with perfect distinctness, not a long hollow archway, the small arch representing the *farther end*, but a short conical solid, with the small end *toward the observer.* Thus the binocular perspective entirely overbears the mathematical.

The cause of this reversal of the natural perspective is shown in the following diagrams. In Fig. 51 the mounting is reversed, as seen by the fact that the points b and b' in the background are nearer together than the points a and a' in the foreground. By combining these in a stereoscope, the background is seen nearer the observer at B, and the foreground thrown farther back to A. In Fig. 52 the pictures are mounted suitably for viewing in the stereoscope, but are combined by the naked eye. Here also the perspective is reversed, for the background is seen at a nearer point B, and the foreground at a farther point A.

This inverse perspective is easily brought out, not only in stereoscopic diagrams, but in nearly all stereoscopic pictures, even in those representing extensive and complex views. In these, of course, when viewed in the stereoscope, the binocular is in harmony with other forms of perspective, and each enhances the effect of the other. But if we combine with the naked eyes by squinting, or if we reverse the mounting and view again with the stereoscope, there is in either case a complete discordance between the binocular and other forms of perspective. In some cases the ordinary perspective is too strong for the binocular, and the only result is a kind of confusion of the view; but in others the binocular completely overbears all opposition and reverses the perspective, often producing the strangest effects.

Fig. 51.

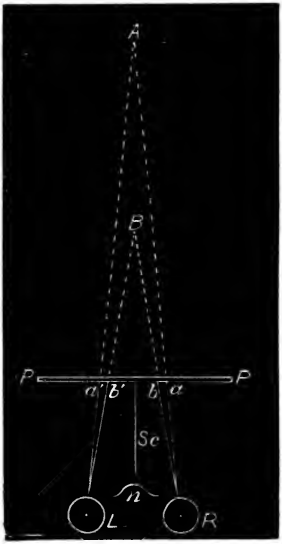
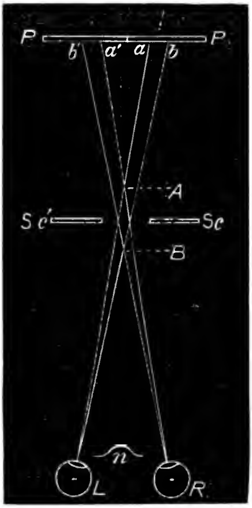
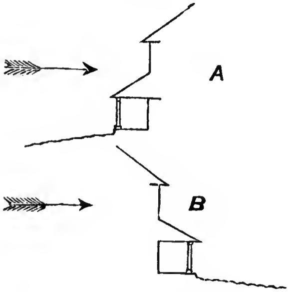


Fig. 52.



For example, I now take up a stereoscopic card representing a building with extensive grounds in front. I view it in a stereoscope. The natural perspective comes out beautifully—the fine building in the background, the sloping lawn in the middle, and a piece of statuary and a fountain in the foreground. I now combine the same with the naked eyes by squinting. As soon as the combination is perfect and the vision distinct, the house is seen in front, and through a space in the wall the statue and fountain are seen behind. Observing more closely, all the parts of the house, the slope of the roof, and the slope of the lawn are also reversed. In Fig. 53, *A* and *B* show the natural and the inverted perspective in section, and the arrows the direction in which the observer is looking. In the one case the roof and the lawn slope downward and toward the observer; in the other, downward and away from the observer. In the one case the building is a solid object; in the other it is an inverted shell, and we are looking at the interior of the shell.

Fig. 53.



In nearly all stereoscopic views I can thus invert the perspective by naked-eye combination. Almost the only exceptions are views looking up the streets of cities. Here the mathematical perspective is too strong to be overborne. Stereoscopic pictures of the full moon are quite common. If these be viewed in a stereoscope, we have the natural perspective, viz., the appearance of a globe; if combined with the naked eyes by squinting, we have a hollow hemisphere. If the mounting be reversed, then the hollow is seen in the stereoscope and the solid globe with the naked eyes. We will give one more example. I have now a stereoscopic view of the city of Paris, but not looking up the streets. When viewed in the stereoscope, the perspective is natural and perfect; the large houses are in the foreground and below, and the others gradually smaller and higher, until the dimmest and smallest are on the uppermost part and form the distant background. I am looking on the *upper surface* of a receding *rising* plane full of houses. I now combine the same pictures with the naked eyes by squinting. As soon as the combined image comes out clear, I see the smallest and dimmest houses on the upper part of the scene, but nearest to me. I am looking on the *under side* of a receding *declining* plane, on which the houses grow larger and larger in the distance, until they become largest at the lowest and farthest margin of the plane. If the mounting of the pictures be reversed, then the natural perspective will be seen with the naked eyes, and the inverse perspective just described will be seen in the stereoscope.

The extreme accuracy of our judgment of relative distance by binocular perspective is well shown by the combination, either by the naked eyes or by the stereoscope, of apparently identical figures on a flat plane. For example, in combining with the naked eyes the figures of a regularly figured wall-paper or tessellated pavement, the least want of perfect regularity in the size or position of the figures is at once detected by an appearance of gentle undulations or more abrupt changes of level. This fact is made use of in detecting counterfeit notes. If two notes from the same plate be put into a stereoscope and identical figures combined, the combination is absolute and the plane of the combined images is perfectly flat; but if the notes be not from the same plate, but copied, slight variations are unavoidable, and such variations will show themselves in a gently wavy surface.

Different Forms of Perspective.—In order to bring out in stronger relief the distinctive character of binocular perspective, it is necessary to mention briefly the several different forms of perspective. There are many ways in which we judge of the relative distance of objects in the field of view, all of which may be called modes of perspective.

1. *Aërial Perspective.*—The atmosphere is neither perfectly transparent nor perfectly colorless. More and more distant objects, being seen through greater and greater depths of this medium, become therefore dimmer and dimmer and bluer and bluer. We judge of distance in this way; and if the air be more than usually clear or more than usually obscure, we may misjudge.

2. *Mathematical Perspective.* — Objects become smaller and smaller in appearance, and nearer and nearer together, the farther away they are. Thus streets appear narrower and narrower, and the houses lower and lower, with distance. Parallel lines of all kinds, such as railway stringers, bridge timbers, etc., converge more and more to a vanishing point.

3. *Monocular or Focal Perspective.*—Objects at the distance of the point of sight are distinct, the lenses being focally adjusted for that distance; but all objects beyond or within this distance are dim. Now, we are aware of a greater or less effort of adjustment to make a distinct image, according to the nearness or the distance of the object looked at. This is also a means of judging of the distance especially of near objects.

These three forms may all be called *monocular;* for they would equally exist, and we could judge of distance, so far as these modes are concerned, equally well, if we had but one eye. But there is still another, viz.:

4. *Binocular Perspective.*—In order to combine the images of objects near at hand, we converge the optic axes strongly; for more distant objects, less and less according to their distance. By this constant change of axial adjustment necessary for single vision, the point of optic convergence is run rapidly back and forth; and thus, by a kind of rapid and almost unconscious triangulation, we estimate the relative distance of objects in the field of view. The man with only one eye can not judge by this method, and thus often misjudges the distance of near objects. In rapidly dipping a pen into an inkstand, or putting a stopper into a decanter, the one-eyed man can not judge so accurately as the two-eyed man. If we shut one eye and attempt to plunge the finger rapidly into the open mouth of a bottle, we are very apt to overreach or fall short.

As clearness of vision is confined to a small area about the point of sight, and rapidly fades away with increasing distance in any direction on the same plane, so clearness and singleness of vision are confined to the distance of the point of sight, and images become dim and double in passing beyond or to this side of that point. Again, as we sweep the point of sight about laterally over a *wide* field of view, and gather up all the distinct impressions into one mental image, so we run the point of optic convergence back and forth, and gather up a mental picture of the relative distance of objects, in a *deep* field.

These different forms of perspective operate for very different distances. The focal adjustment becomes imperceptible for distances greater than about 20 feet. Judgments based on this, therefore, are limited within that distance. Binocular perspective operates perceptibly for much greater distance, perhaps several hundred yards; but beyond this it becomes imperceptible. The other two forms, the mathematical and aërial, operate without limit.

Now the painter can imitate the aërial perspective. He skillfully diminishes the brightness, dulls the sharpness of outline, and blues the tinge of all objects, in proportion to their supposed distance, so as to produce the effect of depth of air. He can also and still more perfectly imitate the mathematical perspective, by diminishing the size of objects and the distance between them as he passes from his foreground to his background. But he can not imitate the focal perspective, and still less can he imitate the binocular perspective. This is artificially given only in the stereoscope, and is the glory of this little instrument. Focal perspective is unimportant to the painter, because imperceptible at the distance at which pictures are usually viewed; but the want of binocular perspective in paintings interferes seriously with the completeness of the illusion. Therefore the illusion is more complete and the perspective comes out more distinctly when we look with only one eye. In a natural scene it is exactly the opposite: the perspective is far more perfect with both eyes open, because then all the forms coöperate.

CHAPTER IV.

THEORIES OF BINOCULAR PERSPECTIVE.

Wheatstone's Theory.—To Wheatstone is due the credit of having discovered the fact that two slightly dissimilar pictures—dissimilar in the same way as the two retinal images of a solid object or of a scene—when united, produce a visual effect similar to that produced by an actual solid object or an actual scene. He also invented the stereoscope to facilitate the combination of such pictures. His theory of these effects was as follows: In viewing a solid object or a scene, two slightly dissimilar images are formed in the two eyes, as already explained; but the mind completely unites or *fuses them into one.* Whenever there occurs such complete mental fusion of images really dissimilar in this particular way, and therefore incapable of mathematical coincidence, the result is a perception of depth of space, or solidity, or relief. In the stereoscope, therefore, he supposes that the two slightly dissimilar pictures are mentally fused into one, and hence the appearance of depth of space follows as the necessary result of this mental fusion.

This theory is still widely held by even the most recent and best physiologists; but it is evidently the result of imperfect analysis of visual impressions. In stereoscopic *diagrams* it is always possible to detect the doubling on which the perception of depth of space is based. It is a little more difficult in ordinary stereoscopic *pictures*, and in natural scenes; but practice and close observation will always detect it in these also. It is most difficult of all to detect it in the case of single *solid objects;* but this is mainly because the doubling of the edges of such objects is usually out of the line of sight. Even where we can not detect the doubling, and yet binocularly perceive depth of space, such perception must be regarded as an example of unconscious cerebration. We actually ground our judgments upon impressions which do not emerge into clear consciousness.

Observe the degrees of this unconsciousness. Even the doubling of the forefinger, when held up before the eyes while we gaze at the wall, is undetected by some persons. To such the binocular perspective here seems to be a simple primary sense-perception. But the slightest scientific observation is sufficient to separate this apparently simple impression into its component elements, and thus to show that it is a judgment based on simpler elements. Next, the doubling of objects in the foreground of a scene or stereoscopic picture, when the background is regarded, fails to appear in consciousness. But analysis again shows that the perception of depth here also is not simple, but decomposable into simpler elements. Close observation again detects the elements on which judgment is based. Therefore, where we can not detect the simpler elements, we must believe that they still exist and that judgments are based upon them. Nothing can be more certain than that complete fusion never takes place; and if it seems so to us, it is only because we do not observe and analyze with sufficient care.

Wheatstone's theory therefore seems true only to the unpracticed and unobservant. It makes that simple and primary which is capable of analysis into simpler elements. It is therefore a popular, not a scientific theory. It cuts, but does not loose, the Gordian knot.

Brücke's Theory.—Brücke and Brewster and Prévost, by more refined observation and more careful analysis, easily perceived that there was in reality no mental fusion of two dissimilar images. Their view, most completely expressed by Brücke,* is that which has been assumed in the foregoing account and explanation of binocular phenomena. It is, that in regarding a solid object or a natural scene, or two stereoscopic pictures in a stereoscope, the eyes are in incessant unconscious motion, and the observer, by alternately greater and less convergence of the axes, combines successively the different parts of the two pictures as seen by the two eyes, and thus by running the point of sight back and forth reaches by *trial* a distinct perception of binocular perspective or binocular relief, or depth of space between foreground and background.

That double images are really necessary to binocular perspective, as maintained by Brücke, is abundantly proved by the experiments already given on that subject. But one additional experiment may be given here to complete the proof.

Experiment.—As I look out of my window, I see the clothes-lines of a neighboring family, about 40 feet distant. Two of these are parallel, but one about 5 or 6 feet beyond the other. The lines being *horizontal*, no double images are visible when the head is erect. In this position I am unable to tell which line is the farther off. But when I turn the head to one side, so that the interocular line is at right angles to the cords,

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* "Archives des Sciences," tome iii, p. 142 (1858).

immediately their relative distance comes out with great distinctness.

This theory is a great advance on the preceding. It is really a scientific theory, since it is based on an analysis of our visual judgments. It is also in part a true theory, and for this reason, in anticipation of what we believe to be a more perfect theory, we have used it in the explanation of many visual phenomena in the preceding pages. But it is evidently not the whole truth, as we now proceed to show.

1. If we place one object before another in the median plane of sight, even when we look steadily and without change of optic convergence at the one or the other, we distinctly perceive the depth of space between them. Evidently no *trial* combination, no running of the point of sight back and forth, and successive union and disunion of the images, are necessary for the perception of binocular relief. But if it be said that change of optic convergence does indeed take place, only rapidly and unconsciously, I proceed to prove that such is not the case.

2. *Dove's Experiment.*—The instantaneous perception of binocular relief is demonstrated by the now celebrated experiment of Dove. If a natural object, or a scene, or two stereoscopic pictures, be viewed by the light of an electric spark or a succession of electric sparks, the perspective is perfect, even though the duration of such a spark is only $\frac{1}{24000}$ of a second of time. On a dark night the relative distance of objects is perfectly perceived by the light of a flash of lightning, which according to Arago lasts only $\frac{1}{1000}$,[*] and according to Rood $\frac{1}{500}$[†] of a second. It is inconceiva-

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[*] Arago, "Œuvres Complètes," tome iv, p. 70.

[†] Rood, "American Journal of Science and Arts," vol. i, 1870, p. 15.

ble that there should be any change of optic convergence, any running of the point of sight back and forth, in the space of $\frac{1}{24000}$ part of a second. Evidently, therefore, binocular perspective may be perceived without such change of convergence. This point is certainly one of capital importance. The instantaneous perception of relief is fatal to Brücke's theory in its pure unmodified form. I have therefore repeated Dove's experiment with care, varying it in every possibly way, so as to guard against every source of error. These experiments completely confirm Dove's result, and establish beyond doubt the instantaneous perception of binocular relief. From a large number of experiments I select a few of the most conclusive and most easily repeated. The spark apparatus used was a Ritchie's Ruhmkorff capable of producing sparks 12 inches long. A Leyden jar was introduced into the circuit to increase the brilliancy of the sparks.

Experiment 1.—I select stereoscopic pictures in which other forms of perspective are wanting, or nearly so; skeleton geometric diagrams are the best. Standing in a perfectly dark room, and viewing these in a stereoscope by the light of a succession of sparks, the perspective is perfectly distinct with two eyes, but not at all with one eye.

Experiment 2.—I select a stereoscopic card like the last, except that mathematical perspective is also strong—such, for example, as a view of the interior of a bridgeway. Of course, as in the last case, the natural perspective is instantly perceived in the stereoscope; but this might be attributed to the mathematical perspective. But now hold the card in the hand and unite the pictures with the naked eyes by squinting: the inverse perspective described on page 135 will be brought out with perfect clearness with two eyes, but the natural perspective (mathematical) returns when we shut one eye. This experiment is conclusive, being removed from even the suspicion of the effect being the result of other forms of perspective; for in this case the binocular is opposed to all other forms of perspective, overbears them, and reverses the perspective.

So much for combination of stereoscopic pictures, whether beyond the plane of the card, as in the stereoscope, or on this side the plane of the card, as in naked-eye combination by squinting. We will next try the viewing of natural objects, eliminating as before as much as possible other forms of perspective.

Experiment 3.—Let two objects, as two brass balls, of the same size, be hung by invisible threads, one about 5 or 6 feet distant, and the other about 1 foot farther. At this distance focal adjustment is practically the same for the two balls, and thus this mode of judging of relative distance is eliminated. Let the balls be placed in the median plane of sight, or nearly so, in such wise that their relative distance may be easily detected with two eyes, but not with one. In the latter case—i. e., with one eye—they look like two balls side by side, the one a trifle larger than the other. Now, after darkening the room, try the experiment by the instantaneous flash of electric sparks. It will be found that under these conditions also the relative distance is perceived with perfect clearness with two eyes, but not with one.

It is certain, then, that binocular perspective is perceived instantly, and therefore without the *trial* combinations of different parts of the two images, as maintained by Brücke, Brewster, and others.

Between the two rival theories, therefore, the case stands thus: Wheatstone is right in so far as he asserts immediate or instantaneous perception of relief, but wrong in supposing that there is a complete mental fusion of the two images. Brücke is right in asserting that binocular perspective is a judgment based on the perception of double images, but wrong in supposing change of optic convergence and successive trial combinations of different parts of the two images to be a necessary part of the evidence on which judgment is based.

My own View is an attempt to bring together and reconcile what is true in both of the preceding views. This, which I conceive to be the only true and complete theory, is hinted at, but not distinctly formulated, by Helmholtz.* I have strongly insisted upon it in all my papers on this subject. I quote from one of them: † "All objects or points of objects, either beyond or nearer than the point of sight, are doubled, but *differently*—the former homonymously, the latter heteronymously. The double images in the former case are united by *less* convergence, in the latter case by *greater* convergence, of the optic axes. Now, the observer knows *instinctively and without trial*, in any case of double images, whether they will be united by greater or less optic convergence, and therefore never makes a mistake, or attempts to unite by making a wrong movement of the optic axes. In other words, *the eye* (*or the mind*) *instinctively distinguishes homonymous from heteronymous images, referring the former to objects beyond, and the latter to objects this side of, the point of sight.*" Or again: In case of double images, "each eye, as it were, knows its own image," although such knowledge does not emerge into distinct consciousness.

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* "Optique Physiologique," p. 939 *et seq.*

† "American Journal of Science and Arts," vol. ii, 1871, p. 425.

Thus, then, I conclude that the mind perceives relief *instantly*, but not *immediately ;* for it does so *by means of double images*, as just explained. This is all that is absolutely necessary for the perception of relief; but it is probable—nay, it is certain—that the relief is made clearer by a ranging of the point of sight back and forth, and a successive combination of the different parts of the object or scene or pictures, as maintained by Brücke.

Return to the Comparison of the Eye and the Camera.—It is time now to return to, and to continue, our comparison of the eye and the photographic camera. We have seen that both the camera and the eye are equally optical instruments contrived for the purpose of making an image; but we have also seen that in both this image is only a means by which to attain a higher end, viz., to make a photographic picture in the one case, and to accomplish distinct vision in the other. In both also, in order to accomplish its higher purpose, there must be a sensitive receiving plate, viz., the iodized silver plate in the one, and the living retina in the other. In both, finally, there are wonderful changes, chemical or molecular, or both, in the sensitive plate. Let us then continue the comparison.

1. In the photographic camera when accomplishing its work there are *three* images which may be mentally separated and described. First, the *light-image.* This is what we see on the ground-glass plate. It comes and goes with the object in front. It is the facsimile in form and color of the object, but diminished in size and inverted in position. Second, the *invisible image.* When the ground-glass plate is withdrawn and the sensitive plate substituted, the light-image falling on this plate determines in it wonderful molecular changes,

which are graduated in intensity exactly according to the intensity and kind of light in the light-image: the aggregate effect is therefore rightly called an image, though it is invisible. Third, the *visible image*, or *picture*. The operator then takes the plate with the invisible image to a dark room, and applies certain chemicals which *develop* the image—i. e., which determine certain permanent chemical changes, which in intensity and kind are exactly proportioned to the antecedent molecular changes, and therefore graduated over the surface exactly as the molecular changes of the invisible image were graduated, and hence also exactly as the light of the light-image was graduated. This is the permanent photographic picture—the facsimile in form of the object which produced it.

So also in the work of the eye, vision, we may mentally separate and may describe three corresponding images. First, there is the *light-image*, which is formed in the dead as well as the living eye. Second, the *invisible image*. The light-image, falling on the sensitive living retina, determines in its substance molecular changes which are graduated in intensity and kind exactly as the light of the light-image is graduated in intensity and color, and may therefore be rightly called an image, even though it be invisible, and the nature of the molecular changes be inscrutable. Third, the *external visible image*. The invisible image, or the molecular changes which constitute it, is transmitted to the brain, and by the brain or the mind is projected outward into space, and hangs there as a visible external image, the sign and facsimile in form and color of the object which produced it.

2. Again, as there are certain effects which can not be produced by one camera—as two cameras from two

positions take two slightly different pictures of the same object or the same scene, which when combined in the stereoscope produce the clear perception of depth of space—even so the two eyes act as a double camera in taking and a stereoscope in combining two slightly different images of every object or scene, so as to give a clear perception of binocular perspective.

We have thus carried the comparison as far as comparison is possible. But there is this essential difference between the two—essential because found everywhere between human and natural mechanism: In the one case we trace mechanism and physics and chemistry throughout. In the other we also trace mechanism, exquisite mechanism, but only to a certain point, beyond which we discover something higher than mere mechanism. We trace physics and chemistry to a certain point, but as we pursue the investigation we find something superphysical and superchemical, or else a physics and a chemistry far higher than any we yet know. At a certain point molecular and chemical change is replaced by *sensation*, *perception*, *judgment*, *thought*, *emotion*. We pass suddenly into another and wholly different world, where reigns an entirely different order of phenomena. The connection between these two orders of phenomena, the material and the mental, although it is right here in the phenomena of the senses, and although we bring to bear upon it the microscopic eye of science, is absolutely incomprehensible, and must in the very nature of things always remain so. Certain vibrations of the molecules of the brain, certain oxidations, with the formation of carbonic acid, water, and urea, on the one side, and there appear on the other sensations, consciousness, thoughts, desires, volitions. There are, as it were, two sheets of blotting paper pasted together; the one is the brain, the other is the mind. Certain ink-scratches and ink-blotchings, *utterly meaningless*, on the one, soak through and appear on the other as *intelligible writing.* But how or why we know not, and can never hope even to guess.

CHAPTER V.

JUDGMENT OF DISTANCE, SIZE, AND FORM.

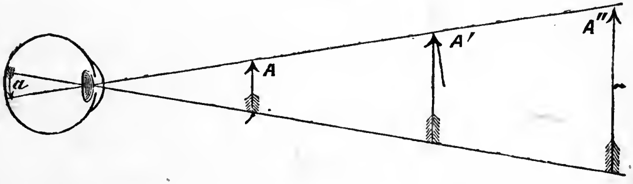
We are now prepared to understand the modes of estimating *distance*, *size*, and *form;* for these modes are founded partly on monocular and partly on binocular vision.

As already stated, the direct and simple sense-impressions given by the optic nerve are *light*, its *intensity*, its *color*, and its *direction.* These can not be analyzed into simpler elements, but distance, size, and form are judgments based upon these.

Distance.—We judge of distance by means of the different forms of perspective already described on page 142: 1. By *focal adjustment*, or monocular perspective. The eye adjusts itself for distinct vision for all distances from infinite distance to five inches. By experience we know distance from the amount of effort necessary to adjust for perfect image, and therefore distinct vision. Judgments based on this are tolerably accurate from 5 inches to several yards. Beyond 20 feet it is too small to be appreciable. 2. By *axial adjustment*, or binocular perspective. The greater or less amount of optic convergence necessary to produce single vision is a far more accurate mode of judging of distance than the last. It is reliable from near the root of the nose to the distance of two or three hundred yards. Beyond this it also becomes inappreciable, for the doubling of objects is only equal to the interocular distance. 3. By *mathematical perspective.* By diminution of the apparent size of known objects and the convergence of parallel lines we judge of distance with great accuracy and almost without limit. 4. By *aërial perspective.* Change of color and brightness of all objects, in proportion to the depth of air looked through, is still another mode of judging of distance, which, though far less accurate than the last, like it extends without limit. Estimates of distance, being judgments, are liable to error. Such errors are often called deceptions of sense, but they are not so. They are errors of judgment based upon *true deliverances* of sense.

Size.—The size of an unknown object is judged by its angular diameter, or the size of its retinal image

FIG. 54.



multiplied by its estimated distance. For example, an image *a*, Fig. 54, occupies a certain space on the retina. Now, evidently, precisely the same image would be made by a small object at *A*, or a proportionally larger similar object at *A′*, or a still larger similar one at *A″*. Therefore the estimated size of the object which produced the image will depend upon the distance we imagine the object to be from us, this distance being of course estimated by the different forms of perspective given above. Thus, estimates of size and distance are very closely related to each other, and an error in the one will involve an error in the other. If we misjudge the distance of an unknown object, we will to the same degree and in the same direction misjudge its size: if our estimate of distance be too great, our judgment of size will also and to the same extent be too great; if our estimate of distance be too small, so also will be our judgment of size. Contrarily, if we make a mistake as to the size of a known object—as, for example, if we mistake a boy for a man—we will also to the same extent misjudge the distance.

Very many illustrations may be given of this general principle, but by far the most perfect are the experiments on combination of the regular figures given on pages 114 and 115. In combining by squinting, in proportion as the point of optic convergence, and therefore the imagined place of the pattern, becomes nearer and nearer, the figures of the pattern become smaller. On the other hand, when we combine beyond the plane of the pattern, so that the more distant point of optic convergence makes the imagined place of the pattern farther off than its real place, then the figures are magnified in the same proportion. So also stereoscopic scenes are larger or smaller than the actual picture, according as we combine beyond or on this side the plane of the picture.

Illustrations like the above are most conclusive, because the relation of size and distance is seen to be mathematically proportioned; but many familiar illustrations may be given.

1. While intently regarding the paper on which I am writing, or the page which I am reading, a fly or gnat passes across the extreme margin of the field of

view toward the open window. I mistake it for a large bird like a hawk flying at some distance in the open air. The reason is, that under these conditions we have no means of judging either of form or of distance; the size and distance of an object are therefore left wholly to the suggestions of the imagination. If we look around so as to see the form distinctly, and to bring binocular or other forms of perspective to bear on the subject, we quickly detect our error and correct our judgment.

2. Where there are no means of judging of distance, we can not estimate size, and different persons will estimate differently. Thus, the sun or moon seems to some persons the size of a saucer, to some that of a dinner-plate, and to some that of the head of a barrel. But under peculiar conditions we imagine them much larger. For example, a pine-tree stands on the western horizon about a mile distant. I am accustomed to judge of the *size* and distance of trees. This one seems to me at least 20 feet across the branches. The evening sun slowly descends and sets behind the tree. It *fills and much more than fills its branches.* Again, here in Berkeley, on a clear day, the Farallone Islands, 40 miles distant, are distinctly seen through the Golden Gate. I think no one would say that the larger one seems less than 100 feet across. At certain seasons in spring and autumn the sun sets behind the Farallones, and these islands are projected in clear outline as black spots on his disk.

3. Illustrations meet us on every side. In fog, objects look larger, because, through excess of aërial perspective, we overestimate distance. On the high Sierra, or the Colorado mountains, or anywhere on the high interior plateau, the clearness of the air and consequent distinctness of distant objects are such, that we imagine

objects to be nearer and therefore smaller than they really are.

Form.—*Outline form* is a combination of directions of component radiants. In a ring of stars, the direction of each star is given immediately; the combination of these several directions gives the ring. This is so simple and immediate a judgment, that it may almost be called a direct sense-perception. It is apparently a direct perception of the *form of the retinal image.* It is so sure and immediate that it is not liable to error; yet it is capable of analysis into simpler elements, as shown above.

Solid form is a far more complex judgment, and therefore liable to error. We judge of solid form partly by binocular perspective and partly by shades of light. The roundness of a column is perceived partly by the greater optic convergence necessary to see distinctly the nearer central parts than the farther marginal parts, and partly by the shading of light on the different parts. The latter effect can be perfectly imitated by the painter, but not the former. Hence the illusion produced by the painter is most perfect at a distance where binocular perspective is very small, but is destroyed by near approach. Hence also the roundness of a painted column is most perfect when looking with one eye, but of a natural column when looking with two eyes.

Gradation of Judgments.—*Intensity*, *color*, and *direction* of light are simple impressions which can not be further analyzed. Next come *outline form* and *surface contents*, which may indeed be analyzed into combination of directions, but yet the perception is so direct and so certain that it may well be called immediate. Next comes *solid form*, which, as we have seen, is a more complex judgment based on simple elements, and therefore may be deceived. Next come the closely related and still more complex judgments of *size and distance*, which are therefore still more liable to error. These latter judgments become more and more complex as the objects in the field of view become more numerous and more complex in form and varied in position; as, for example, the judgments of form, size, and distance of all the objects in an extended natural scene. All these seem to the uninstructed as immediate instinctive perceptions, and mistakes are supposed to be the result of deceptions of sense instead of errors of judgment, as they really are. Judgments like these, which are so quickly made that the process has largely dropped out of consciousness, I shall call *visual judgments.* But these higher and more complex visual judgments pass, by almost insensible degrees, into still higher and more complex *intellectual judgments.* Thus from simple sense-impressions we pass without break through the various grades of visual judgments to the lower intellectual judgments, and from these again through various grades of complexity to the highest efforts of the cultured mind.

Now, as visual judgments seem to the uninstructed primary, immediate, and simple perceptions, so also among intellectual judgments many seem to those uninstructed in psychology and unskilled in mental analysis as primary, immediate, instinctive, or innate, and therefore certain. But, as the study of visual phenomena teaches that these visual judgments are capable of analysis into simpler elements, and therefore liable to error, so also the study of psychology should teach us that many of the so-called instinctive judgments, primary intuitions, etc., may also be capable of analysis, and therefore liable to error. Further, it is evident that the so-called facts of consciousness, in the one field as in the other, can not be considered reliable until subjected to rigid analysis. The study of visual (especially binocular visual) phenomena is peculiarly valuable: first, in teaching us that so called immediate intuitions are in many cases only judgments, the processes of which have dropped out of consciousness; and, second, in teaching us the habit of analysis of such apparently simple intuitions.

RETROSPECT.

We have now given in clear outline the most important phenomena of vision and their explanation. It will not be amiss, before proceeding further, to look back over what we have passed, and justify its logical order.

There are three essentially different modes of regarding the eye, which must be combined in a complete account of this organ. We have taken up these successively. First, we treated of the *eye as an optical instrument* contrived to form a perfect image, every focal point of which shall correspond with a radiant point in the object. This is a purely physical investigation. Second, we treated of the *structure of the retina*, especially its bacillary layer, and showed how from this structure resulted the wonderful property of corresponding points *retinal* and *spatial*, and the exchange between these by impression and perceptive projection, and how the law of direction and all the phenomena of monocular vision flow out of this property. Third, we treated of the still more wonderful correspondence of the *two retinæ* point for point, and therefore of their spatial representatives point for point; and considered how by ocular motion the two images of the same object are made to fall on corresponding points of the two retinæ, and their spatial representatives are thereby made to coincide and become one; and how, finally, all the phenomena of binocular vision flow from this property.

We have therefore apparently covered the ground originally laid out. But there are still a number of questions on binocular vision, somewhat more abstruse and more disputed than the preceding, but of so high interest that they must not be wholly neglected. The remaining chapters will be devoted to these.

Omit chapters
1, 2, & 3

PART III.

ON SOME DISPUTED POINTS IN BINOCULAR VISION.

CHAPTER I.

LAWS OF OCULAR MOTION.

SECTION I.—LAWS OF PARALLEL MOTION.—LISTING'S LAW.

We have already (page 69) spoken of spectral images produced by strong impressions on the retina. It is evident that these, being the result of impressions branded upon the retina and remaining there for some time, must while they remain follow all the motions of the eye with the greatest exactness. They are specially adapted, therefore, for detecting motions of the eyes, such as slight torsions or rotations on the optic axes, which could not be detected in any other way.

Experiment 1.—Let the experimental room be darkened by closing the shutters, but allow light to enter through a vertical slit between the shutters of one window. Standing before the window with head erect, gaze steadily at the slit until a strong impression is branded in upon the *vertical meridian* of the retina. If we now turn about to the blank wall, we see a very distinct colored vertical spectral image of the slit. Placing now the eyes in the primary position—i. e., with face perpendicular and eyes looking horizontally—if, without changing the position of the head, we turn the eyes to the right or left horizontally, the image remains vertical. Also if we turn the eyes upward or downward by elevating or depressing the visual plane, the image remains vertical. But if, with the visual plane *elevated* extremely, say 40°, we cause the eyes to travel to the right or left, say also 40°, or if we turn the eyes from their original primary position obliquely upward and to one side to the same point, the image is no longer vertical, but leans decidedly to the *same* side; i. e., in going to the right, the image leans to the right, thus— / ; in going to the left, it leans to the left, thus— \ . If, on the contrary, the visual plane be *depressed*, then motion of the eyes to the right causes the image to lean to the left, thus— \ ; while motion to the left causes it to lean to the right, thus— / .

Experiment 2.—If, instead of a vertical, we use a horizontal slit in the window, and thus obtain a horizontal image and throw it on the wall as before, then, if the image has been made with the eyes in the primary position, it will be seen on the wall perfectly horizontal. Furthermore, if the eyes travel right and left in the primary visual plane, or upward and downward by elevating or depressing the visual plane, the image retains its perfect horizontality. But if, with the visual plane elevated, we cause the point of sight to travel to the one side or the other, the image is seen to turn to the *opposite* side; i. e., when the eyes turn to the right, the image turns to the left, thus—╱; when they turn to the left, the image rotates to the right, thus—╲. If the visual plane be *depressed*, then motion to the right causes the image to rotate to the right (╲), and motion to the left causes it to rotate to the left (╱).

These rotations of the image depend wholly on the oblique position of the eyes, and it makes no difference how that oblique position is reached—whether by motion along rectangular coördinates, as in the experiments, or by oblique motion from the primary position. Furthermore, the amount of rotation of the image increases with the amount of elevation or depression of the visual plane, and the amount of lateral motion of the eyes.

Experiment 3.—The fact of rotation or torsion of the images, and the direction of that torsion, are easily determined by the somewhat rough methods detailed above; but if we desire to *measure the amount of torsion*, the wall or other experimental plane must be covered with rectangular coördinates, vertical and horizontal. By experimenting in this way, I find that for extreme oblique positions the torsion of the vertical image on the vertical lines of the experimental plane is about 15°, but the torsion of the horizontal image on the horizontal lines is only about 5°. The reason of this difference will be explained farther on.

Putting now all these results together, the following diagram (Fig. 55) gives the position of the vertical and horizontal images when projected on a vertical plane for all positions of the point of sight. Simple inspection of the diagram is sufficient to show that the inclination or torsion of the vertical image on the true verticals, and that of the horizontal image on the true horizontals, are in *opposite directions.* If torsion of the images show torsion of the eye, there must be a fallacy somewhere. The one or the other must be wrong; for when one indicates torsion to the right, the other indicates torsion to the left, and *vice versa.* To show this contradictory testimony more clearly, and thus to prove that there is a fallacy here, we make another experiment.

FIG. 55.

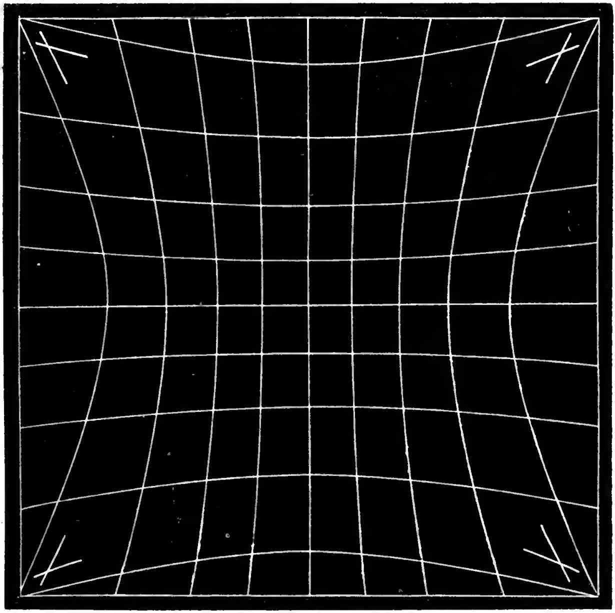
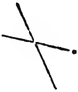


DIAGRAM SHOWING THE INCLINATION OF VERTICAL AND HORIZONTAL IMAGES FOR ALL POSITIONS OF THE POINT OF SIGHT.

Experiment 4.—Make a rectangular cross-slit in the window, gaze steadily upon it until the spectral impression is made on the retina, and then cast the image on the wall. In the primary position of the eyes it is of course a perfect rectangular cross. Now turn the eyes to the extreme upper right-hand corner of the wall. The cross, by opposite rotations of the two parts, is seen distorted thus—. Looking upward and to the left, it is seen thus—. Oblique motion downward and to the right makes it appear thus—, and to the left thus—. It will be observed that this is exactly the manner in which the lines cross in the diagram, and we have placed crosses in the corners to indicate that fact.

Evidently the cause of the contradictory evidence of the two images is *projection* on a plane inclined at various angles to the line of sight. The diagram is a correct representation of the phenomena as seen projected on a vertical plane, but is not a correct representation of the torsions of the eyes. To eliminate this source of fallacy and get the true torsion of the eyes, we must project the cross-image on a plane in every case perpendicular to the line of sight.

Experiment 5.—Prepare an experimental plane a yard square, make a rectangular cross in the center, and set up a perfectly perpendicular rod at the point of crossing. Fix the plane in a position inclined 30° to 40° with the vertical, and obliquely to the right side and above, so that, when sitting before the experimental window and turning the eyes extremely upward and to the right, the observer looks directly on the top of the rod, and this latter is projected against the plane as a round spot. We thus know that the line of sight is perpendicular to the plane. Now, after gazing at the cross-slit in the window until the spectral impression is made on the retina, without moving the head, cast the image on the center of the plane by turning the eyes obliquely upward and to the right. The rectangular cross-image rotates, *both parts alike*, so as to retain perfectly its rectangular symmetry, to the right, thus—, showing unmistakably a torsion of the eyes in the same direction. If the plane be arranged similarly on the left side, the cross turns to the left, thus—. If the plane be arranged below and to the right, so that the eyes turned obliquely downward and to the right shall look perpendicularly upon it, the cross will turn to the left, thus—. If similarly arranged on the left side, the cross will turn to the right, thus—. In all cases the rectangular symmetry is perfectly preserved, a sure sign that there is no error by projection, and that they truly represent the torsion of the eyes.

Experiment 6.—In order to neglect no means of testing the truth of this conclusion, we will make one more experiment, using the sky as the plane upon which to project the image. This spatial concave is of course everywhere at right angles to the line of sight, and therefore is free from any suspicion of error from projection. Standing in the open air before a vertical flag-staff, I gaze upon it steadily until its image is, as it were, burned into the vertical meridian of the retina. Now, without moving the head, I turn the eyes obliquely upward and to the right, and the image leans decidedly to the right; and turning to the left, the image leans to the left. In this position of the head, of course, the ground prevents us from making the same experiment with the visual plane depressed. I therefore vary the experiment slightly. Sitting directly in front of the college building, with the morning sun shining obliquely on its face, the light-colored perpendicular pilasters gleam in the sunshine, and contrast strongly with the shadows which border their northern margin. Gazing steadily at the building, I easily get a strong spectral image of the whole structure, with its vertical and its horizontal lines. Now throwing myself flat on my back, I see the image perfectly erect on the zenith. Turning the eyes upward toward the brows and to the right and left, then downward toward the feet and to the right and left, the whole image of the building rotates precisely as indicated in my previous experiments.

Evidently, then, in the diagram Fig. 55, the *verticals* give true results, but the *horizontals* deceptive results by projection. Why this is so is easily explained. Suppose an observer to stand in a room before a vertical wall; suppose him further to be surrounded by a spherical wire cage constructed of rectangular spherical coordinates, or meridians and parallels, with the eye in the center and the pole in the zenith. Evidently, the surface of this spherical concave is everywhere perpendicular to the line of sight, and therefore, like the sky, is the proper surface of projection. Evidently, also, the meridians and parallels everywhere at right angles to each other are the true coördinates wherewith to compare the images, vertical and horizontal, in order to determine the direction and amount of their rotation. Now the simple question is, "How do these true rectangular coördinates project themselves on the wall to an eye placed in the center, or how would their shadows be cast by a light in the center?" It is evident that the meridians would project as straight verticals, but the parallels not as straight lines, but as *hyperbolic curves*, increasing in curvature as we go upward or downward. The diagram Fig. 56 shows how the

Fig. 56.

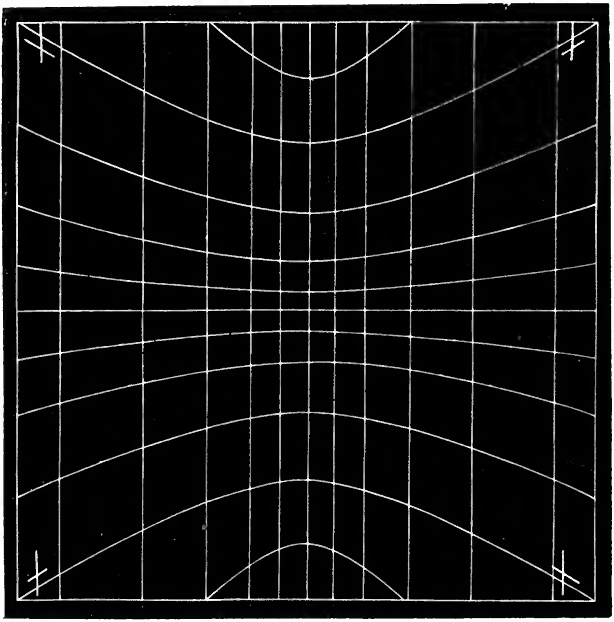
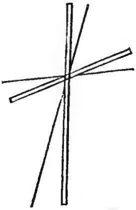


Diagram showing the Projection of a System of Spherical Coördinates on a Vertical Plane.

spherical coördinates would project on a vertical wall. By calculation or by careful plotting it may be shown that at an angle of elevation or depression of 40°, and a lateral angle of the same amount, the inclination of the hyperbolic curve on the horizontals of the wall will be about 20°. Now a rectangular cross-image, if *unrotated*, would project as the crosses in the corners; i. e., the vertical arm would project vertically, but the horizontal arm would be inclined 20° with the horizontal, so that the angles of the cross would be about 70° and 110°. Now rotate these crosses 15°, the right upper one to the right, the left upper one to the left, the right lower to the left, and the left lower to the right, and we have the precise phenomena represented by the diagram Fig. 55; i. e., the verticals are turned 15° right or left as the case may be, and the horizontals in the opposite direction, but only 5°. Fig. 57 illustrates this in the case of the right-hand upper cross-image—the heavy cross representing the cross unrotated, and the lighter one the same rotated 15° to the right by extreme obliquity of the line of sight.

FIG. 57.



Therefore, the diagram which truly represents the torsion of the eye in various positions, or the torsion of the cross-image when referred to a spherical concave perpendicular to the line of sight in every position, is represented in Fig. 58. Simple inspection of this figure shows the real direction and amount of rotation both of the vertical and the horizontal image for every position of the line of sight. The crosses in the corners show that there is no distortion by projection.

We are justified therefore in formulating the laws of parallel motion of the eyes thus:

1. *When the eyes move together in the primary plane to the one side or the other, or in a vertical plane up or down, there is no rotation on the optic axes, or torsion.*

FIG. 58.

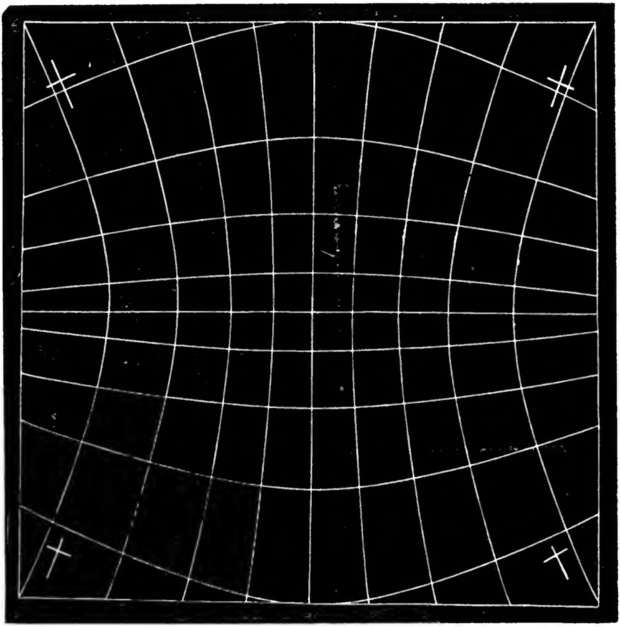


DIAGRAM SHOWING THE TRUE TORSION OF THE EYE FOR VARIOUS POSITIONS OF THE POINT OF SIGHT.

2. *When the visual plane is elevated and the eyes move to the right, they rotate to the right; when they move to the left, they rotate to the left.*

3. *When the visual plane is depressed, motion of the eyes to the right is accompanied with rotation to the left, and motion to the left with rotation to the right.*

4. These laws may be all generalized into one, viz.: *When the vertical and lateral angles have the same*

sign,[*] *the rotation is positive* (*to the right*) *; when they have contrary signs, the rotation is negative* (*to the left*).

The law now announced as the result of experiment is evidently identical with the *law of Listing*, which has been formulated by Listing himself thus:

"*When the line of sight passes from the primary position to any other position, the angle of torsion of the eye in its second position is the same as if the eye had come to this second position by turning about a fixed axis perpendicular both to the first and the second position of the line of sight.*" [†]

Now an axis which satisfies these conditions can be none other than an *equatorial axis*, or at least *an axis in a plane perpendicular to the polar axis.* In turning from side to side in the primary plane, it is a vertical equatorial axis. In turning up and down vertically, it is a horizontal equatorial axis. In turning obliquely, as in the experiments on torsion, it is an oblique equatorial axis. Now take a globe, and, placing the equator in a vertical plane, make a distinct vertical and horizontal mark across the pole. Then turn the globe on an oblique equatorial axis, so that the pole shall look upward and to the right. It will be seen that the polar cross is no longer vertical and horizontal, but is *rotated to the right.* If the globe be turned upward and to the left, the polar cross will rotate to the left; if downward and to the right, it will rotate to the left; and if to the left, it will rotate to the right. In a word, the rotation in every case is the same as given in the above laws determined by experiment.

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[*] In reference to a vertical line, positions to the right are positive and to the left negative; in reference to a horizontal line, above is positive and below negative.

[†] Helmholtz, "Optique Physiologique," p. 606.

Contrary Statement by Helmholtz.—We have given these laws and their experimental proof in some detail, and have taken some pains to show that they are in complete accord with Listing's law, because Helmholtz in his great work on "Physiological Optics" has given these laws of ocular motion the very reverse of mine. I quote from the French edition of 1867, which is not only the latest but also the most authoritative edition of the work:

"When the plane of sight is directed upward, lateral displacements to the *right* make the eye turn to the *left*, and displacements to the left make it turn to the right.

"When the plane of sight is depressed, lateral displacements to the *right* are accompanied with torsion to the *right*, and *vice versa*.

"In other words, when the vertical and lateral angles are both of the same sign, the torsion is *negative*; when they are of contrary signs, the torsion is *positive*." *

We have demonstrated the very reverse of every one of these propositions, and we have also shown that they are inconsistent with Listing's law as quoted by Helmholtz himself. The experiments by which Helmholtz seeks to determine the torsions of the eye are the same as those already described under experiments 1 and 2, page 165. The results which he reaches are also the same as those reached by myself, except that he makes the inclination of the vertical image on the verticals of the wall, and of the horizontal image on the horizontals of the wall, equal to each other, while I make the inclination of the verticals much greater. The diagram by which he embodies all these results is also similar to my diagram, Fig. 55, except that in his the horizontal and

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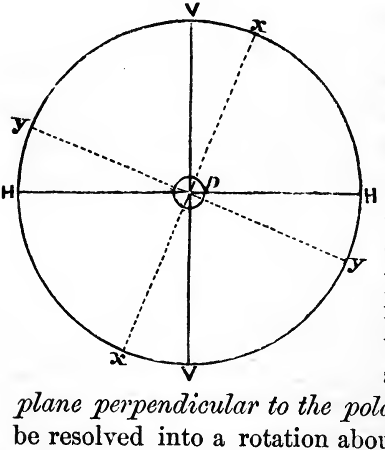
* "Optique Physiologique," p. 602.

vertical curves are exactly similar, while in mine the curves of the verticals are much greater. He also, like myself, admits that there is a fallacy by projection. But unaccountably he imagines that the inclination of the horizontal image on the true horizontal gives true results, and the inclination of the vertical image on the true vertical deceptive results by projection; therefore he imagines the eye to turn exactly the reverse of the reality. Experiments 5 and 6, under conditions eliminating errors by projection, prove the falseness of his results. The reader who desires to follow up this subject will find it discussed in an article by the writer referred to below.*

The Rotation only Apparent.—There can be no doubt, then, that when the eye passes from its primary position to an oblique position, the vertical meridian of the retina is no longer vertical, but inclined. If we observed the iris of another person, we should see that it had turned as a wheel. In deference to the usage of other writers and to the appearance, I have spoken of this as a *rotation on the optic axis*, but it is so in appearance only, and not in reality; for the motion of the eye, being always on an axis *in a plane perpendicular to the polar or optic axis*, can not be resolved into a rotation about that axis. A simple experiment will show the kind of rotation which takes

Fig. 59.



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* "American Journal of Science and Arts," III, vol. xx, 1880, p. 83.

place in bringing the eye to an oblique position. Take a circular card, Fig. 59, and make on it a rectangular cross which shall represent the vertical (*V V*) and horizontal (*H H*) meridians of the retina. A small central circle *p* represents the pupil. Now take hold of the disk with the thumb and finger of the right hand at the points *V V*, and place this line in a vertical plane. Then tip the disk up so that the pupil *p* shall look upward 45° or more, but the line *V V* still remaining in the vertical plane. Finally, with the finger of the left hand turn the disk on the axis *V V* to the left. It will be seen that *V V* is no longer vertical, nor *H H* horizontal; but some other line *x x* is vertical, and *y y* horizontal. In other words, the whole disk seems to have rotated to the left. But this is evidently *no true* rotation on a polar axis, but only an *apparent* rotation consequent upon *reference to a new vertical meridian of space.* It does not take place in the primary plane, because there all the spatial meridians are parallel, but only in an elevated or depressed plane, because the spatial meridians are there convergent. I shall therefore hereafter call this apparent rotation on the optic axis *torsion.* This is the more important, because there is a real rotation on the optic axis, which we shall speak of under the next head.

SECTION II.—LAWS OF CONVERGENT MOTION.

We have thus far confined ourselves to explanation of the laws which govern the eyes when they move in the *same direction* with axes parallel, as in looking from side to side or up and down. I have called this the law of *parallel motion.* We now come to speak of the laws which govern the eyes when they move in *opposite directions*, as in convergence. These I will call the laws of *convergent motion.*

In convergence there is not merely an *apparent* rotation or torsion, but a *real* rotation of the eyes on the optic axes; and since the motions are in *opposite* directions, the rotations are also opposite. But, except in very strong convergence, the rotation is small and difficult to observe, and therefore has been either overlooked or denied by many observers. As the existence or non-existence of this rotation has an important bearing on the much-vexed question of the horopter, it is important that proof should be accumulated even to demonstration.

The first difficulty which meets us in experimenting on this subject is, that spectral images, which are such delicate indicators of ocular motion, are almost useless here. In parallel motion of the eyes these images follow every movement with the utmost exactness, but in convergent motion they do not. Suppose, for example, with the eyes parallel or nearly so, a spectral image is branded on the vertical meridians of both eyes. In convergence each eye may move through 45° or more, but the place of the spectral image is the same, viz., *directly in front.* The eye also in extreme convergence may rotate on the optic axis 10°, but the vertical image remains still perfectly vertical. The reason of this is, that the two retinal images are on corresponding points, and therefore by the law of corresponding points their external representatives are *indissolubly united.* In moving the eyes in opposite directions, it is impossible that the images should move except by separating; but separation, either complete or partial, is impossible without violating the law of corresponding points—a law which is never violated under any circumstances whatsoever. Actual objects therefore, not spectral images, must be used in these experiments.

As the experiments about to be described are among the most difficult in the whole field of binocular vision, and as in many of them it is absolutely necessary that the primary visual plane should be perfectly horizontal, I must first define what we mean by the *primary visual plane*, and show how it may be made perfectly *horizontal.*

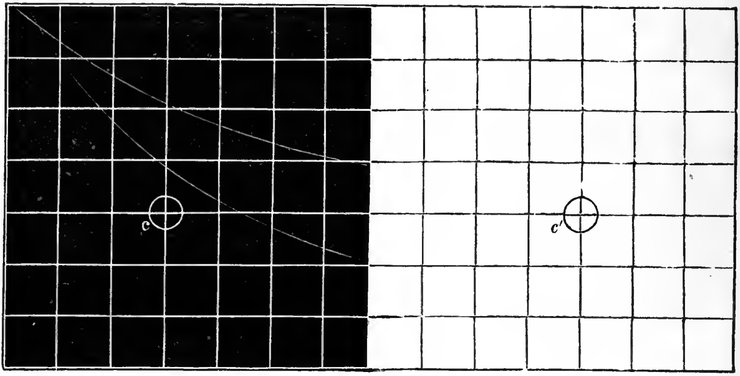
Take a thin plate, like a cardboard; place its edge on the root of the nose and the card at right angles to the line of the face, in such wise that the plane of the card shall cut through the center of the two pupils, and you can see only its edge. The card is then in the primary visual plane. Keeping the position of the card fixed in relation to the face, the face may be elevated or depressed, and the card will be also elevated or depressed, but will remain in the primary visual plane. But if the card be elevated or depressed so as to make a different angle with the line of the face, then the visual plane is elevated or depressed above or below the primary position. When the head is erect and the line of the face vertical, the primary visual plane is horizontal. Suppose we wish now to look at a vertical wall in such wise that the primary visual plane shall be perfectly horizontal. We first mark on the wall a horizontal line exactly the height of the root of the nose. Standing then say 6 feet off, and shutting first one eye and then the other, we bring the image of the lowest part of the root of the nose directly across the line. The primary plane is

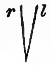
FIG. 60.

then perfectly horizontal. In Fig. 60, *n* and *n′* are the curves of the outline of the root of the nose as seen by the right and left eye respectively, and *n n′* is the horizontal line on the wall. We are now prepared to make our experiments.

Experiment 1.—Prepare a plane 2 feet long and 1 foot wide. Dividing this by a middle line into two equal squares, let one of the halves be painted black and the other white. Let the whole be covered with rectangular coördinates, vertical and horizontal, on the black half the lines being white and on the white half black, as in Fig. 61. Near the middle of the two square halves, and at the crossing of a vertical and horizontal line, make two small circles, *c c′*. Set up this plane on the table in a perfectly vertical position, and at a distance of 2 or 3 feet. Rest the chin on the table immediately in front of the plane, with a book or other support under the chin, so that the root of the nose shall be exactly the same height as the circles, which in this case is about 6 inches. Now, shutting alternately

Fig. 61.

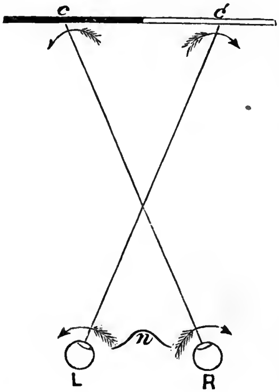


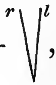
one eye and the other, bring the image of the lowest part of the root of the nose coincident with the horizontal line running through the circles. The primary plane is now perfectly horizontal, and therefore at right angles to the experimental plane. Now, finally, converge the eyes until the right eye looks directly at the left circle, and the left eye at the right circle, and of course the two circles combine. If one is practiced in such experiments, and observes closely, he will see that the vertical lines of the two squares (which can be readily distinguished, because those of the one are white and of the other black), as they approach and pass over one another successively, are not perfectly parallel, but make a small angle, thus— 

; and also that the angle increases as the convergence is pushed farther and farther, so that lines even beyond the circles are brought successively together. Similarly also the horizontals cut each other at a small angle, but this fact is not so easy to observe as in the case of the verticals.

Such are the phenomena; now for the interpretation. It must be remembered that images of objects differ wholly from spectral images in this, viz.: that spectral images, being fixed impressions on the retina, follow the motions of the eye with perfect exactness; while, images of objects being movable on the retina, their external representatives in convergence seem to move in a direction contrary to the motions of the eye (page 107). This is true of all motions, whether by transfer of the point of sight or by rotation about the optic axes. Now, in the above experiment, the images of the two squares with all their lines seem to rotate about the point of sight outward—i. e., the right-hand square to the right, and the left-hand square to the left. At first sight this might seem to indicate a contrary rotation of the eyes, viz., inward. But not so; for, observe, the field of view of the right eye is the left or black square, and the field of view of the left eye is the right or white square. The right-eye field turns to the left, showing a rotation of the right eye to the right; while the left-eye field turns to the right, showing a rotation of the left eye to the left. *Thus the two eyes in convergence rotate outward.* This is shown in the diagram Fig. 62, in which c c' is the experimental plane. The arrows show the direction of rotation of the images of the plane and of the eyes.

Fig. 62.



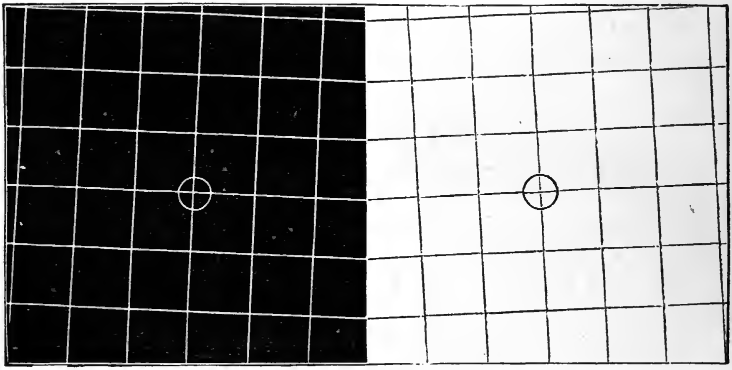
Experiment 2.—When one becomes accustomed to experiments of this kind, he can make them in many ways. I find the following, one of the easiest and most convenient: Measure the exact height of the root of the nose upon the sash of the open window, and mark it. Stand with head erect about 3 or 4 feet from the window. Using the cross-bars of the sash-frame as horizontal lines, arrange the head so that the two images of the root of the nose shall be exactly the same height as the mark. The primary plane is now horizontal. Now converge the eyes until the dark outer jambs or sides of the frame of the sash approach each other. This will be very distinct on account of the bright light between them. It will be seen that the frames come together, not parallel, but as a sharp V, thus— , r and

l being the right- and left-eye images respectively. I find that when I stand at a distance from the window equal to the width of the sash, the angle between the two jambs as they come together is about 15°, showing a rotation of each eye outward 7° 30′. When standing still nearer, so that the convergence is extreme, the angle is 20° or more, showing a rotation of each eye of 10° or more.

In all these experiments the extremest care is necessary to insure the perfect horizontality of the visual plane. The slightest upward or downward looking vitiates the result by introducing mathematical perspective. If there were no rotation, then looking upward and converging would bring the jambs together by perspective, thus—$_{r}\bigwedge_{l}$; looking downward, thus—$^{r}\bigvee^{l}$; looking horizontal, parallel, thus—$\|$. But on account of rotation, looking horizontal brings them together thus—$^{r}\bigvee^{l}$; downward, at higher angle, thus—$^{r}\bigvee^{l}$. Looking upward more and more, the angle decreases till it becomes 0 (i. e., the jambs parallel), and then inverted. I find that in the previous experiment, standing from the window the distance of its width, I must elevate the plane of vision about 6°—i. e., I must look about 8 or 9 inches above the mark—to make the jambs parallel. This is therefore a good method of measuring amount of rotation.

Experiment 3.—A far more accurate mode of measuring the amount of rotation is by constructing diagrams on a plane similar to the one used in experiment 1, but in which the verticals and horizontals are both inclined on the true verticals and true horizontals in a direction contrary to the rotation of the eyes—i. e., inward—and then determining the degree of convergence necessary to make them come together *perfectly parallel.* I find that for my eyes, when the verticals are thus inclined in each square 1¼° with the true vertical, and therefore make an angle of 2½° with each other (Fig. 63), they come together parallel when the point of sight is 7 inches from the root of the nose. When the angle of inclination in each is 2½° with the true vertical, and therefore 5° with each other, the point of sight must be 4 inches off. When the inclination with the true vertical is 5°, and therefore 10° with each other, the point of sight is 2·2 inches. Finally, when the inclination with the true vertical is 10° or 20° with each other, then they can be brought together parallel only by the extremest convergence, the point of sight being then only a quarter of an inch in front of the root of the nose. In the diagram Fig. 63 the lines, both vertical and horizontal, are inclined inward 1¼°, and therefore the verticals of the two squares make an

Fig. 63.

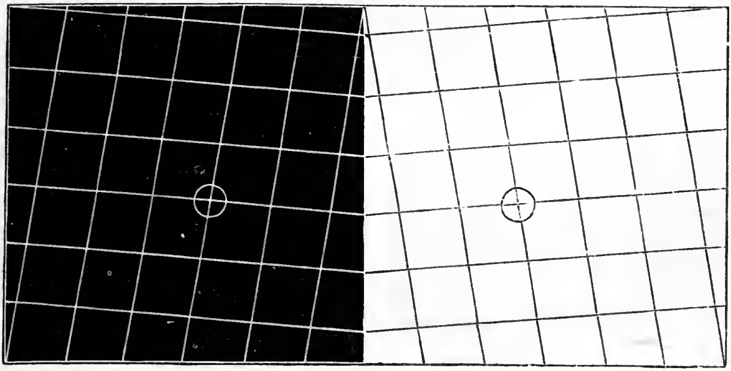


Verticals and Horizontals inclined 1¼°.

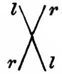
angle with each other of 2½°. It is therefore a reduced facsimile of the plane used. The coördinate lines coincide when the point of sight is 7 inches from the root of the nose.

In the cases of extreme convergence mentioned above, I find that for perfect coincidence of both verticals and horizontals it is necessary that the inclination of the verticals with the true vertical must be greater than that of the horizontals with the true horizontal; so that the little squares are not perfect squares. Thus, when the verticals incline 5°, the horizontals must incline only 3¾°; when the verticals incline 10°, the horizontals incline only 5°. Fig. 64 is a reduced facsimile of this last case of extreme convergence. I can not account for this, except by a distortion of the ocular globe by the unusual and unnatural strain on the muscles, especially the oblique muscles of the eyes. It may be that other eyes are more rigid than mine, and suffer less distortion.

Fig. 64.



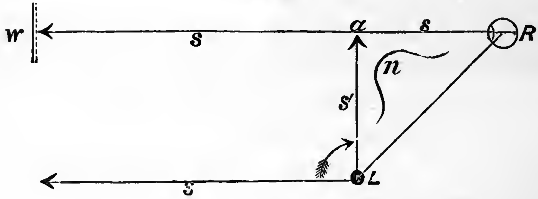
Verticals inclined 10°, Horizontals 5°.

The above is by far the most refined method of proving rotation, and of measuring its amount. But so difficult are these experiments, and so delusive the phenomena, that it is necessary to prove it in many ways. Another method is by means of *ocular spectra.* We have already shown that these are not so well adapted to experiments in convergent motion as they are in parallel motion. For example, two brands on the vertical meridians of the two retinæ produce spectral images which are perfectly united (p. 178). Now in strong convergence, when the two eyes rotate outward, the two images will not separate or cross each other, thus— 

, as we might at first expect; for this is forbidden by the law of corresponding points. But we may use a spectral image of *one* eye to show rotation of that eye.

Experiment 4.—The manner in which I conduct the experiment is as follows: I make a vertical spectral image in the manner already explained (page 164), by gazing with one eye (say the right) on a vertical slit in a closed window. I now turn about, and, keeping the left eye *L*, Fig. 65, still shut, I look across the root of the nose *n* with the right eye *R* at a perfectly vertical line *w* on the wall. I see the vertical image perfectly parallel and nearly coincident with the vertical line on the wall. Then, while the right eye still continues to look along the line *R s*, I turn the shut left eye *L* from

FIG. 65.



its previous position $L\ s$ through an angle of 90°, until its line of sight is $L\ s'$. In other words, I run the *point of sight* or point of convergence from the distant point of the wall w along the line $R\ s$ to the point a near the root of the nose. When I do so, I see the spectral image incline to the right, thus— /, indicating (since the image is *spectral*) a rotation of the eye in the *same* direction. This experiment is very difficult, but it is conclusive.

Experiment 5.—I shut one eye, say the left, and look across the root of the nose at a distant object, as in Fig. 63. An assistant now observes attentively my iris, and notes with care the position of the radiating lines. Now, without changing at all the direction of the *line* of sight, I change the *point* of sight to an object or point very near the root of the nose, as in Fig. 63, by turning the optic axis of the shut eye through 90°. I again relax the convergence so as to make the optic axes *parallel*, and again converge upon the near point; and so on alternately. With every convergence the iris is seen to rotate like a wheel *outward.* I have subjected my eyes to the observation of five different persons, and they all made the same statement in regard to the direction of rotation.

There can be no longer any doubt that my eyes in convergence rotate on the optic axes outward, the degree of rotation increasing with the degree of convergence. To generalize this as a law of ocular motion I have found extremely difficult, because there are so few persons who are able to verify the results, on account of imperfect voluntary control of the ocular muscles, and especially the difficulty or even impossibility which most persons find in observing intelligently images which are not at the point of sight. Nevertheless, I have found several persons who by considerable practice have been able to confirm nearly all these experiments. I have also made observations directly on the eyes of other persons in the manner described in the fifth experiment, and noted the rotation of the iris in strong convergence. I think, therefore, I am justified in announcing the outward rotation of the eyes in convergence as a general law.

The Effect of Elevation and Depression of the Visual Plane on Rotation.—The question next occurs, What is the effect, on this rotation, of elevation or depression of the visual plane? I have also made many experiments to determine this point.

Experiment 6.—In making experiments of this kind, all that is necessary is that the experimental plane shall be exactly perpendicular to the visual plane. This may be insured either by keeping the face in its former position and changing the inclination of the plane, or else, more conveniently, by fixing the plane in its vertical position and changing the inclination of the face. If we choose the latter method, then, for experiments with the visual plane elevated, the head or face is turned downward and the eyes look upward toward the brows upon the experimental plane —care being taken that the eyes in their new position shall be on a level with the center of the plane. By experiments of this kind I find that the outward rotation in convergence, especially in strong convergence, *increases* decidedly for the same degree of convergence with the elevation of the visual plane.

Experiment 7.—For experiments on rotation with the visual plane depressed, the face must be turned upward (taking care as before that the eyes in their new position are on a level with the center of the plane), and then the eyes look downward toward the point of the nose upon the experimental plane. In this case I find that for the same degree of convergence the rotation decreases steadily, until it becomes zero for all degrees of convergence when the visual plane is depressed 45° below its primary position—i. e., when the eyes look toward the point of the nose. Below this angle the rotation seems to be inverse—i. e., inward—although it is impossible to try this with strong convergence, because the nose is in the way.

Cause of the Rotation.—It is probable that the rotation is produced by the action of the inferior oblique muscles. If so, we can understand why it increases with elevation of the visual plane, and decreases with its depression; for in the first case the tension on these muscles would be increased, while in the latter case it would be decreased.

Previous Researches on this Subject.—The only writer who has to my knowledge made experiments on rotation of the eyes in convergence is Meissner.* The results he arrives at are substantially the same as my own; but he arrives at them indirectly, while investigating the question of the horopter, and by methods far less exact than those employed by myself. My results, therefore, must be regarded as a confirmation and a demonstration of his. Meissner's method will be spoken of under the head of the horopter.

Laws of Parallel and of Convergent Motion Compared.—We will now formulate the laws of convergent motion, and at the same time contrast them with those of parallel motion.

1. When the eyes move in the primary plane in the

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* "Archives des Sciences," tome iii, 1858, p. 160.

same direction (parallel motion), *there is no torsion;* but when they move in that plane in *opposite* directions, as in convergence, they *rotate outward.*

2. When the visual plane is *elevated* and the eyes move in the same direction by *parallel* motion, then lateral motion to the *right* produces torsion to the *right*, and to the *left*, torsion to the *left;* but when, on the contrary, they move in opposite directions, as in *convergence*, then as the right eye moves to the *left*, i. e., toward the nose, it rotates to the *right*, and as the left eye moves toward the nose, i. e., to the *right*, it rotates to the *left*. If Listing's law operated at all in this case, as it acts in the opposite direction, it would tend to neutralize the effects of convergent rotation; but such is not the fact. On the contrary, as we have seen, the outward rotation increases with elevation of the visual plane.

3. When the visual plane is *depressed*, and the eyes move from side to side by *parallel* motion, then lateral motion to the *right* is attended with torsion to the *left*, and motion to the *left* with torsion to the *right*. Also when the eyes move by *convergent* motion in opposite directions, they rotate in the same direction as in the case of parallel motion; but there is this great difference: that while in parallel motion the torsion *increases* with the angle of depression, in convergent motion it *decreases* to zero at 45°. If Listing's law operated at all in this case, it would coöperate with and increase the effect of convergent motion; but the very reverse is the fact, the rotation decreasing with the angle of depression.

4. We have already shown that the so-called torsion of parallel motion is not a true rotation on the optic axes, but only an *apparent* rotation, the result of refer-

ence to a new spatial meridian not parallel with the primary meridian. On the contrary, the rotation produced by convergent motion is a *true* rotation on the optic axes, as shown by the fact that one eye without change of position will rotate in sympathy with the convergent motion of the other eye (experiments 4 and 5).

It is evident, then, that when the eyes move in the same direction parallel to each other, as in ordinary vision of distant objects, then all their motions are governed by Listing's law; but when, on the contrary, they move in opposite directions, as in convergence, then the law of Listing is wholly abrogated, or else overborne, and another law reigns in its place.

CHAPTER II.

THE HOROPTER.

If we look at any point, the two visual lines converge and meet at that point. Its two images therefore fall on corresponding points of the two retinæ, viz., on their central spots. A small object at this point of convergence is seen absolutely single. We have called this point "the point of sight." All objects beyond or on this side the point of sight are seen double—in the one case homonymously, in the other heteronymously—because their images do not fall on corresponding points of the two retinæ. But objects below or above, or to one side or the other side of the point of sight, may possibly be seen single also. *The sum of all the points which are seen single while the point of sight remains unchanged is called the horopter.*

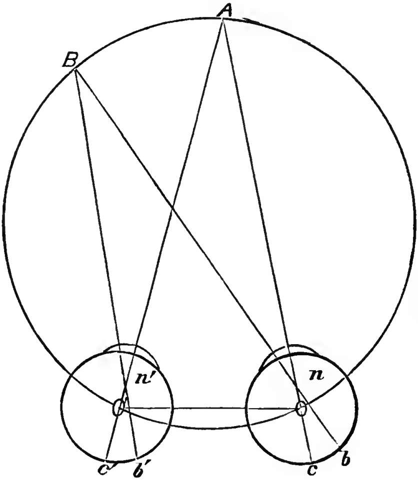
Or it may be otherwise expressed thus: Each eye projects its own retinal images outward into space, and therefore has its own field of view crowded with its own images. When we look at any object, we bring the two external images of that object together, and superpose them at the point of sight. Now the point of sight, together with the images of all other objects or points which coalesce at that moment, lie in the horopter. The images of all objects lying in the horopter fall on corresponding points, and are seen single; and conversely, the horopter is the surface (if it be a surface) of single vision.

Is the horopter a *surface*, or is it only a *line?* In either case, what are its form and position? These questions have tasked the ingenuity of physicists, mathematicians, and physiologists. If the position of corresponding points were certainly known, and invariable in reference to a given spatial meridian, then the question of the horopter would be a purely mathematical one. But the position of corresponding points may change in ocular motions. It is evident, then, that it is only on an experimental basis that a true theory of the horopter can be constructed. And yet the experimental determination, as usually attempted, is very unsatisfactory on account of the indistinctness of perception of objects except very near the point of sight. Therefore experiments determining the laws of ocular motion, and mathematical reasoning based upon these laws, seem to be the only sure method.

The most diverse views have therefore been held as to the nature and form of the horopter. Aguilonius, the inventor of the name, believed it to be a *plane* passing through the point of sight and perpendicular to the median line of sight. Others have believed it to be the *surface of a sphere* passing through the optic centers and the point of sight; others, a *torus* generated by the revolution of a circle passing through the optic centers and the point of sight, about a line joining the optic centers. The subject has been investigated with great acuteness by Prévost, Müller, Meissner, Claparède, and finally by Helmholtz. Prévost and Müller determine in it, as they think, the circumference of a circle passing through the optic centers and the point of sight.

(the horopteric circle), and a line passing through the point of sight and perpendicular to the plane of the circle (horopteric vertical). The horopteric circle of Müller is shown in Fig. 66, in which *O O′* is the line between the optic centers, *n n′* the nodal points or points of ray-crossing, *A* the point of sight, and *B* an

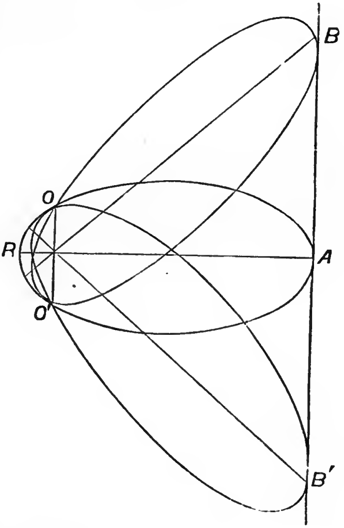
FIG. 66.



object to the left and situated in the circumference of the circle. Of course, the images of *A* fall on the central spots *c c′*. It is seen also that the images of *B* fall at *b b′*, at equal distances from the central spots *c c′*, one on the nasal half and one on the temporal half, and therefore on corresponding points. The *horopteric vertical* of Müller passes through *A* and perpendicular to the plane of the circle (i. e., of the diagram).

Claparède makes the horopter a surface, of such a form that it contains a straight line passing through the point of sight and perpendicular to the visual plane, and also such that every plane passing through the optic centers makes by intersection with this surface the circumference of a circle. In other words, he thinks that the horopter is a surface which contains the *horopteric vertical*, *B A B′*, Fig. 67, and the horopteric circle, *O A O′*, and in addition is further characterized by the fact that the intersection with it of every plane passing through the optic centers *O O′* upward as *O B O′* or downward as *O B′ O′* is also a circle. It is evident that, as these circles increase in size upward and downward, the horopter according to Claparède is a surface of singular and complex form.

FIG. 67.



Helmholtz arrives at results entirely different. According to him, the horopter varies according to the position of the point of sight, and is therefore very complex. He sums up his conclusions thus: *

"1. Generally the horopter is a line of double curvature produced by the intersection of two hyperboloids, which in some exceptional cases may be changed into a combination of two plane curves.

"2. For example, where the point of convergence

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* Croonian Lecture, in "Proceedings of the Royal Society," xiii (1864), p. 197; also "Optique Physiologique," p. 901 *et seq.*

(point of sight) is situated in the median plane of the head, the horopter is composed of a straight line drawn through the point of convergence, and a *conic section* going through the optic centers and intersecting the straight line.

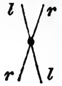
"3. When the point of convergence is situated in the plane which contains the primary directions of both visual lines (primary visual plane), the horopter is composed of a *circle* going through that point and through the optic centers (horopteric circle), and a straight line intersecting the circle.

"4. When the point of convergence is situated both in the middle plane of the head and in the primary visual plane, the horopter is composed of the horopteric circle and of a straight line going through that point.

"5. There is only one case in which the horopter is a *plane*, namely: when the point of convergence is situated in the middle plane of the head and at an infinite distance. Then the horopter is a plane parallel to the visual lines, and situated beneath them at a distance which is nearly as great as the distance of the feet of the observer from his eyes when he is standing. Therefore, when we look straight forward at a point on the horizon, the horopter is a horizontal plane going through our feet; *it is the ground on which we stand.*

"6. When we look not at an infinite distance, but at any point on the ground on which we stand which is equally distant from the two eyes, the horopter is not a plane, but the straight line which is one of its parts coincides with the ground."

Some attempts have been made to establish the existence of the horopteric circle of Müller by means of experiments. A plane is prepared and pierced with a multitude of holes into which pegs may be set. The eyes look horizontally over the plane on one peg, and the others are arranged in such wise that they appear single. It is found that they must be arranged in a circle. I have tried repeatedly, but in vain, to verify this result. The difficulty is the extreme indistinctness of perception at any appreciable distance from the point of sight. But, as a general fact, the results reached by the observers thus far mentioned have been reached by the most refined mathematical calculations, based on certain premises concerning the position of corresponding points and on the laws of ocular motion. We will examine only those of Helmholtz, as being the latest and most authoritative.

Helmholtz's results are based upon the law of Listing as governing all the motions of the eye, and upon his own peculiar views concerning the relation between what he calls the *apparent* and the *real* vertical meridian of the retina. The *real* vertical meridian of the eye is the line traced on the retina by the image of a really vertical linear object when the median plane of the head is vertical and the eye in the primary position. The *apparent* vertical meridian of the eye is the line traced by the image of an apparently vertical linear object in the same position of the eye. This is also called the *vertical line of demarkation*, because it divides the retina into two halves which correspond each to each and point for point. Now, according to Helmholtz, the *apparent* vertical meridian or vertical line of demarkation does not coincide with the *real* vertical meridian, but makes with it in each eye an angle of 1¼°, and therefore with one another in the two eyes of 2½°. The horizontal meridians of the eyes, both real and apparent, coincide completely. Therefore, if the two eyes were brought together in such wise that their *real* vertical and horizontal meridians should coincide, their *apparent* horizontal meridians would also coincide; but the apparent vertical meridians would cross each other at the central spot thus— , making an angle of 2½°. For this reason a perfectly vertical line will appear to the right eye not vertical, but inclined to the left, and to the left eye inclined to the right. In order that a line shall appear perfectly vertical to one eye, it must incline for the right eye 1¼° to the right, and for the left 1¼° to the left. But a horizontal line appears truly horizontal. Therefore an upright rectangular cross will appear to the right eye thus— , and to the left eye thus— . The inclination of these lines is, however, exaggerated. If, therefore, according to Helmholtz, we make a diagram of which one half is composed of black lines on white ground, and the other of white lines on black ground, like those already used, but in which, while the horizontals run straight across horizontally, the verticals on the right half are inclined 1¼° to the right, and on the left half the same amount to the left (Fig. 68), then, on combining these by gazing beyond the plane of the diagram (i. e., with parallel eyes), either with the naked eye or with the stereoscope, the verticals will be seen to come together parallel and unite perfectly.

Now Helmholtz's views of the form of the horopter are based wholly on this supposed relation of real and apparent vertical. Take for example his case of the eyes fixed on a distant point on the horizon. In this case, he says, "the horopter is the ground on which we stand." This is true if the relation above mentioned is

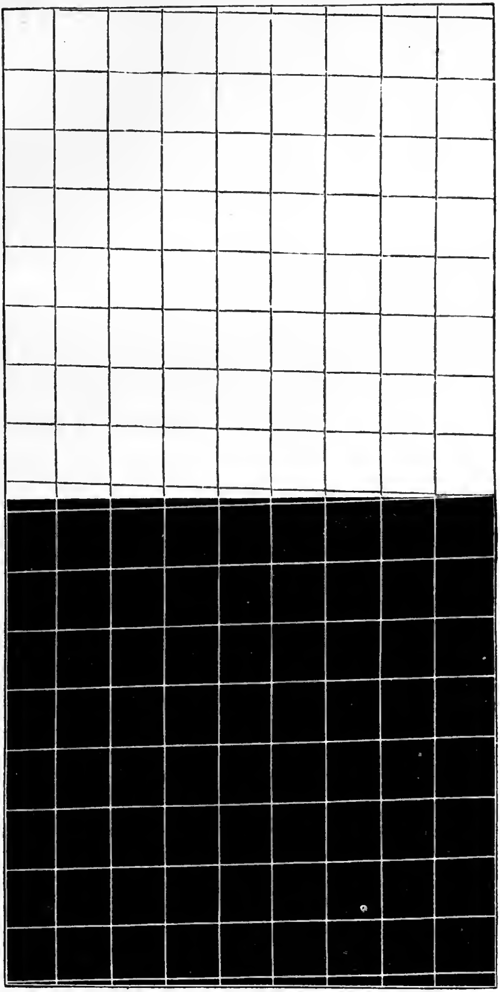
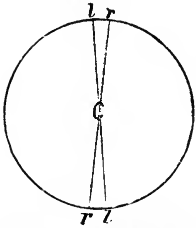


FIG. 68.

true; for, with an interocular distance of 2½ inches, two lines drawn through the optic centers, each inclined 1¼° with the vertical and therefore 2½° with each other, would in fact meet about 5 feet below—i. e., about the feet. If, therefore, we place two actual rods together on the ground between the feet, and the upper ends before the pupils, the eyes being parallel, it is evident that the image of the right rod on the right retina and that of the left rod on the left retina would fall exactly on Helmholtz's apparent vertical meridian, and, if Helmholtz's views be correct, on the vertical lines of demarkation and on corresponding points of the retinæ, and thus would be binocularly combined and seen as a single line lying along the ground to infinite distance. And conversely, with the eyes parallel and the lines of demarkation inclined $1\frac{1}{4}^\circ$ with the vertical, a rod lying on the ground to infinite distance would cast its images on these lines, and therefore be seen single throughout.

There are several curious questions which force themselves on our attention here if Helmholtz's view be true.

Fig. 69.



The Retinæ superposed.—*r r*, line of demarkation of right eye; *l l*, line of demarkation of left eye.

1. If we suppose the two eyes to be placed one on the other, so that the real vertical meridians coincide, we have already seen that Helmholtz's apparent verticals or lines of demarkation will cross each other like an X, as in Fig. 69, making with each other an angle of $2\frac{1}{2}^\circ$. Now the two rods $2\frac{1}{2}$ inches apart at the height of the eyes, and meeting below at the feet, or the rod lying along the ground to infinite distance, would occupy with their images only the upper half of the X. But suppose the two rods, instead of stopping opposite the eyes, to continue upward to the limits of the field of view. Obviously this upper half would cast images on the lower half of the X, and therefore would be seen single also. Where shall we

refer them? Or, to express it differently, the horopter with the eyes looking at a distant horizon, according to Helmholtz, is the ground we stand on; but this is evidently pictured on the upper halves only of the two retinæ. Where is the other half of the horopter corresponding to the lower halves of the retinæ?

2. Again: According to Helmholtz, in looking at a distance the horopter is the ground we stand on, and he gives this as the reason why distance along the ground is more clearly perceived than in other positions.* On the contrary, it seems to me that it would have just the reverse effect. If the horopter were the ground we stand on, then relative distances on the ground could not be perceived by binocular perspective at all; for this is wholly dependent on the existence of double images, which could not occur in this case by the definition of the horopter. It would be therefore only by other forms of perspective that we could distinguish relative distance along the ground. But that we do perceive perspective of the ground binocularly—i. e., by double images—is proved by the fact that the perspective of the receding ground is very perfect in stereoscopic pictures, where the images of nearer points are necessarily double; for the camera has no such distinction between real and apparent verticality as Helmholtz attributes to the eye.

But it is useless to argue the point any further, for I am quite sure that the property which Helmholtz finds in his eye is not general, and therefore not normal. We have seen that in convergence the eyes rotate outward, so as to bring about the very condition of things temporarily which Helmholtz finds permanent in his eyes. I have therefore thought it possible, or

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* *Op. cit.*, p. 923.

even probable, that the same habits in early life which, by constant adapting of the eyes to vision of near objects, finally produce myopy, may also, by constant slight rotation of the eyes outward and distortion in convergence on near objects, finally bring about a permanent condition of slight distortion and outward rotation of 1¼°. Helmholtz is slightly myopic.*

However this may be, I am sure there is no such relation between real and apparent vertical meridian in my eyes as that spoken of by Helmholtz. All the experiments supposed to prove such relation fail completely with me. A vertical rectangular cross appears rectangular to either eye. The lines of Helmholtz's diagram, Fig. 66, when combined beyond the plane of the diagram, either by the naked eyes or by a stereoscope, do not come together parallel, but with a decided angle, viz., 1¼°. But when I turn the diagram upside down, and combine by squinting, then the vertical lines, being inclined the other way, as in my diagram, Fig. 61, combine perfectly by outward rotation of the eyes. I have constructed other diagrams with less and less inclination of the verticals, until the inclination was only 10′, and still I detected the want of parallelism when combined beyond the plane of the diagram. Beyond this limit I could not detect it, but I believe only because the limit of perception was passed; for when the lines are made perfectly vertical, they come together perfectly parallel and unite absolutely. It is certain, therefore, that in my eyes the vertical line of demarkation coincides completely with the true vertical meridian.

Meissner † alone, of all writers with whom I am

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* *Op. cit.*, p. 914.

† Meissner, "Physiologie des Sehorgans"; also "Archives des Sciences," vol. iii (1858), p. 160.

acquainted, attempts to determine the horopter by experiment. According to him, if a stretched thread be held in the median plane at right angles to the primary visual plane, about 6 to 8 inches distant, and the point of sight be directed on the middle, the thread will not appear single, but the two images will cross each other at the point of sight thus—

, *r r′* being the right-eye image, and *l l′* the left-eye image. Now, as the images are heteronymous at the upper end and homonymous at the lower end, it is evident that they will unite at some farther point above and some nearer point below. By *inclining* the thread in the manner indicated—i. e., by carrying the upper end farther and bringing the lower end nearer—the two images come together more and more, until at a certain angle of inclination, varying with the distance of the point of sight, they unite perfectly. The thread is now in the horopter.

Experiment.—I find that the best way to succeed with Meissner's experiment is as follows: Hold a stretched black thread parallel with the surface of the glass of an open window, and within half an inch of it. Now, with the eyes in the primary position, look, not at the thread, but at some spot on the glass. It will be seen that the double images of the thread are not parallel, but make a small angle with each other, thus—

. Now bring the lower end nearer the observer very gradually. It will be seen that the double images become more and more nearly parallel, until at a certain angle of inclination the parallelism is perfect. I have made several experiments with a view to measuring the angle of inclination for different distances of the point of sight. I find that for 8 inches the inclination is about 7° or 8°; for 4 inches, about 8° or 9°. It seems to increase as the point of sight is nearer. But of this increase subsequent experiments make me doubtful.

Meissner's results may be summarized thus:

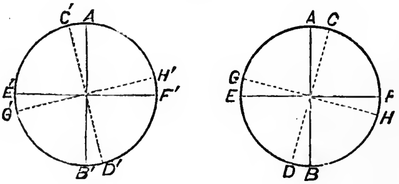
1. With the eyes in the primary position and the point of sight at infinite distance, the horopter is a plane perpendicular to the median line of sight (plane of Aguilonius).

2. For every nearer point of sight in the primary plane, the horopter is not a surface at all, but a *line* inclined to the visual plane and dipping toward the observer, the inclination increasing with the nearness of the point of sight or degree of convergence.

3. In turning the plane of vision *upward*, the inclination of the horopteric line increases. In turning the plane of vision *downward*, the inclination of the horopteric line decreases, until it becomes zero at 45°, and the horopteric line expands into a plane passing through the point of sight and perpendicular to the median visual line.

Furthermore, Meissner attributes these results to a rotation of the eyes on the optic or visual axes *outward*;

Fig. 70.

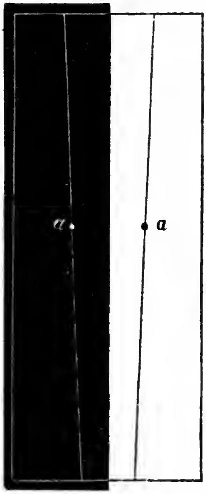


so that the vertical lines of demarkation, $C\,D$, $C'\,D'$, Fig. 70, no longer coincide perfectly with the vertical meridians *A B*, *A′ B′*, nor the horizontal lines of demarkation *G H*, *G′ H′* with the horizontal meridians *E F*, *E′ F′*, as they do when the eyes are parallel, but cross them at a small angle. With eyes parallel, the images of a vertical line will fall on the vertical lines of demarkation (for these then coincide with the vertical meridians) and be seen single. But if the eyes rotate outward in convergence, then the images of a vertical line will no longer fall on the vertical lines of demarkation, and therefore will be seen double except at the point of sight. In order that the image of a line shall fall on the vertical lines of demarkation and be seen single, with the eyes in this rotated condition, the line must not be vertical, but inclined with the upper end farther away and the lower end nearer to the observer. It is evident also that under these circumstances the horopter can not be a surface, but is *restricted to a line.* This requires some explanation.

If the eyes be converged on a vertical line, and then rotated on their optic axes, as we have seen, the line will be doubled except at the point of sight. This doubling is the result of *horizontal* displacement of the two images in opposite directions at the two ends—the upper ends heteronymously, the lower ends homonymously. Now, since heteronymous images unite by carrying the object farther away and homonymous images by bringing it nearer, it is evident that if the line be inclined by carrying the upper end farther and bringing the lower end nearer, the two images will unite completely, and thus form a horopteric line. But all points to the right or left of this horopteric line will also double by rotation of the eyes; but this doubling is by *vertical* displacement, as shown in Fig. 70. Now doubling by vertical displacement can not be remedied by increasing or decreasing distance, *because the eyes are separated horizontally.* It is therefore irremediable. Hence no form of surface can satisfy the conditions of single vision right and left of the horopteric line. Hence, also, the restriction of the horopter to a line, and the inclination of that line on the plane of vision, are necessary consequences of the rotation of the eyes on their viusal axes. This rotation I have already proved in the most conclusive manner by experiments detailed in the last chapter.

It will be seen by reference to the preceding chapter that my results coincide perfectly with those of Meissner, although I was ignorant of Meissner's researches when I commenced my experiments many years ago. The end in view in the two cases, and also the methods used, were different. Meissner was investigating the question of the horopter, and outward rotation of the eyes was the logical inference from the position of the horopter discovered by him. I was investigating the laws of convergent motion, and the nature of the horopter was a logical consequence of the outward rotation which I discovered. Meissner's method is, however, far less refined and exact than mine.

Fig. 71.

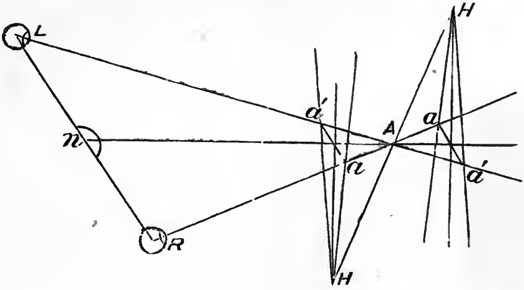


I have also proved the inclination of the horopteric line by direct experiments by my method.

Experiment 1.—If two lines, one black on white and the other white on black, be drawn with an inclination of 1¼° with the vertical, and therefore 2½°

with each other, and the eyes be brought so near to any points *a a*, Fig. 71 (taking care that the visual plane shall be perpendicular to the plane of the diagram), that these shall unite beyond the plane of the diagram at the distance of 7 inches, the two lines will coincide perfectly. If then the diagram be turned upside down, and the lines be again united by squinting—the diagram being in this case a little farther off, so that the point of sight shall again be 7 inches—the coincidence of the lines will be again perfect. Fig. 72—in which *R* and *L* represent the right and left eyes respectively, *a H* and *a′ H* the lines to be combined in these two positions, and *A* the point of sight—will explain how the combination takes place. The line *H A H* is the horopteric line.

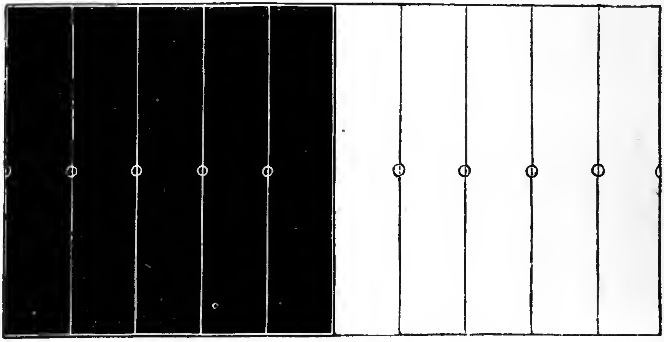
FIG. 72.



This experiment is difficult to make, but I am quite confident of the reliability of the results reached. I made many experiments with different degrees of inclination of the lines *a H*, *a′ H*, and therefore with different degrees of convergence, and many calculations based on these experiments, to determine the inclination of the horopteric line for different degrees of convergence. But the experiments are so difficult that, while in every case the inclination of the horopteric line was proved, the exact angle could not be made out with certainty. It seemed to me about 7° for all degrees of convergence, and therefore for all distances. It certainly does *not* seem to increase with the degree of convergence, as maintained by Meissner.

Experiment 2.—I next adopted another and I think a better method. I used a plane and diagram covered with true verticals only, as in Fig. 73. I placed this, instead of vertical as in previous experiments, inclined 7°, and therefore in the supposed position of the horopter. Placing the face in a vertical position and the plane of vision horizontal—i. e., my eyes at the same height as the little circles—I combined these successively, and watched how the lines came together. I found that when inclined 7° all the lines, even the farthest apart—viz., 30 inches—came together perfectly parallel. I then tried the plane inclined 8°; the parallelism was still complete for all degrees of convergence. But when the plane was inclined 9°, the inclination of the lines in coming together successively

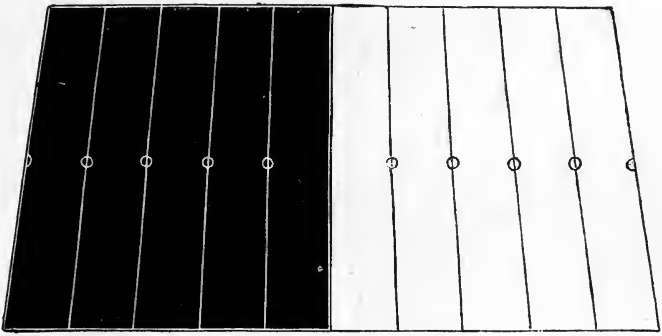
Fig. 73.



was distinctly perceptible. I am sure therefore that the true inclination is about 7° or 8°.

Such are the phenomena; now for the interpretation. It will be observed that when the plane represented by the diagram fig. 73 is inclined to the visual plane, all the vertical lines converge by perspective; the convergence increasing with the distance from the central line, as in Fig. 74, which represents such an inclined plane referred to a plane perpendicular to the visual plane. By calculation and careful plotting, I find that at the distance of 15 inches the convergence of the first two lines, 6 inches apart, for a plane inclined 8°, is each about 1° 31′, or to each other 3° 2′; of the second pair, 12 inches apart, 3° 3′ each, or 6° 6′ to each other; of the third pair, 18 inches apart, 4° 35′ each, or 9° 10′ to each other; of the fourth pair, 24 inches apart, 6° 7′ each, or 12° 14′ to each other; of the fifth pair, 30 inches apart, 7° 40′ each, or 15° 20′ to each other. Therefore, an increasing rotation of the eyes outward is necessary to bring these together parallel. The distance of the point of sight measured from the optic centers varied

Fig. 74.



Projection of Plane inclined 8°.

from 4½ inches in the first to 1¼ inch in the last case; but the inclination of the horopteric line was the same in every case. This is probably the most accurate means of determining by direct experiment both the horopter and the degree of rotation of the eyes for every degree of convergence of the optic axes.

Experiment 3.—I next tried the same experiment with the visual plane depressed 45°, but yet perfectly horizontal. In this position, on combining the vertical lines, I find that they retain perfectly their natural perspective convergence. On decreasing the inclination of the diagram the perspective convergence becomes less and less, until when the plane of the diagram is vertical the lines come together again parallel for all degrees of convergence, as already found in the previous experiment. I conclude therefore that in turning the visual plane downward the inclination of the horopteric line becomes less and less, until when the visual plane is depressed 45° it becomes perpendicular to that plane, and at the same time *expands to a surface.*

In turning the visual plane upward, I find, especially for high degrees of convergence, that I must incline the plane of the diagram more than 8° (viz., about 10°) in order that the lines shall come together parallel. From this I conclude a higher degree of rotation of the eyes and a higher inclination of the horopteric line.

The points on which I do not confirm Meissner are: 1. The increasing inclination of the horopteric line with increasing nearness of the point of sight. I make it constant. 2. I think it probable also that Meissner is wrong in supposing that the horopter, when the visual plane is depressed 45°, is a *plane.* It is certainly a *surface*, but not a plane; for it is geometrically clear that points in a perpendicular *plane* to the right or left of the point of sight can not fall on corresponding points of the two retinæ. The horopter in this case is evidently a curved surface. I do not undertake to determine its nature by mathematical calculation, and the experimental investigation is unsatisfactory for the reason already given, viz., the extreme indistinctness of perception of points situated any considerable distance from the point of sight in any direction.

In regard to the horopter I consider the following points to be well established:

1. As a necessary consequence of the outward rotation of the eyes in convergence, for all distances in the primary visual plane the horopter is a line inclined to the visual plane, the lower end nearer the observer. But whether the inclination is constant, or increases or decreases with distance, I have not been able to determine with certainty. It is probably constant.

2. In depressing the visual plane, the inclination of the horopteric line becomes less and less, until when the visual plane is inclined 45° below the primary position the horopteric line becomes perpendicular to the visual plane, and at the same time expands into a surface. The exact nature of that surface I have not attempted to investigate, for reasons already explained; but it is evidently a curved surface.

3. In elevating the visual plane, especially with strong convergence, the inclination of the horopteric line increases.

Finally, the question naturally occurs: Of what advantage is this outward rotation of the eyes, and the consequent limitation of the horopter to a line? Or is it not rather a defect? Should the law of Listing be regarded as the ideal of ocular motion under all circumstances, and should the departure from this law in the case of convergence be regarded as abnormal? Or is there some useful purpose subserved by the rotation of the eyes on their optic axes? I feel quite sure that there is a useful purpose subserved; for there are special muscles adapted to produce this rotation, and the action of these muscles is consensual with the adjustments, axial and focal, and with the contraction of the pupil. This purpose I explain as follows:

A general view of objects in a wide field is a necessary condition of animal life in its higher phases; but an equal distinctness of all objects in this field would be fatal to that *thoughtful attention* which is necessary to the development of the higher faculties of the human mind. Therefore the human eye is so constructed and moved as to restrict as much as possible the conditions both of *distinct* vision and of *single* vision. Thus, as in *monocular* vision the more elaborate structure of the central spot restricts distinct vision to the visual line, and focal adjustment still further restricts it to a single point in that line, the point of sight, so also in *binocular* vision axial adjustment restricts single vision to the horopter, while rotation on the optic axes restricts the horopter to a single line.

CHAPTER III.

ON SOME FUNDAMENTAL PHENOMENA OF BINOCULAR VISION USUALLY OVERLOOKED, AND ON A NEW MODE OF DIAGRAMMATIC REPRESENTATION FOUNDED THEREON.

In all that I have said thus far, I have made use of the ordinary mode of representing binocular visual phenomena. I have done so because I could thus make myself more easily understood. But it is evident on a little reflection that the usual diagrams do not in any case represent the real *visual facts*—i. e., the facts as they really seem to the binocular observer.

Fig. 75.

Thus, for example, if $\underline{a}$, B, and $\underline{c}$, Fig. 75, be three objects in the median plane, but at different distances, and the two eyes, R and L, be converged on B, as already explained, $\underline{a}$ and $\underline{c}$ will be both seen double—the former heteronymously, the latter homonymously. It will be observed that in the diagram the double images of both $\underline{a}$ and $\underline{c}$ are referred to the plane of sight P P. Now every one who has ever tried the experiment knows that the double images are not thus referred in natural vision; but, on the contrary, they are seen at their real distance, though not in their natural position. Indeed, it is only by virtue of this fact that we have perception of binocular perspective. The diagram therefore, although it truly represents the parallactic position of the double images, does not represent truly their apparent distance. If, on the other hand, we attempt in the diagram to refer the double images to their real distance (observing the law of direction), then they unite and form one, which is equally untrue. Thus, if we represent truly the visual position, we misrepresent the visual distance; if, on the contrary, we try to represent the visual distance, we misrepresent the visual position. It is evident therefore that the usual diagrams, while they represent truly many important visual phenomena, wholly fail to represent truly many others, especially the facts of binocular perspective.

The falseness of the usual mode of representation becomes much more conspicuous if, instead of two or more objects, we substitute a continuous rod or line. In this case the absurdity of projecting the double images on the plane of sight is so evident that it is never attempted. The mode universally used for representing the visual result when a rod is placed in the median plane is shown in Figs. 76–79, of which Fig. 76 represents the actual position of the rod in the median plane, and the actual position of the visual lines when the eyes are fixed on the nearer end *A*; Fig. 77, the same when the eyes are fixed on the farther end *B*; and Figs. 78 and 79, the visual results in the two cases respectively. Now it will be observed that in both these figures representing visual results (Figs. 78 and 79) the image of the rod belonging to each eye is coincident with the visual line of the other eye, and therefore makes an angle with its own visual line equal to the visual angle *R A L*, *R B L*. But this is not true, for Figs. 76 and 77 show that it ought to make but half that angle. If

FIG. 76.

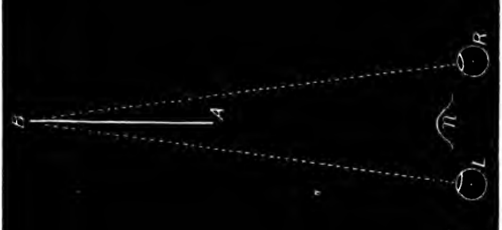


FIG. 77.

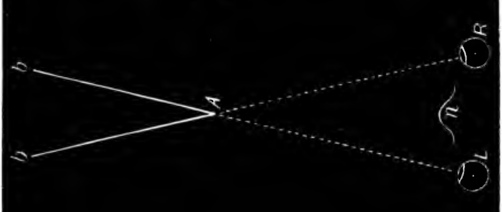


FIG. 78.

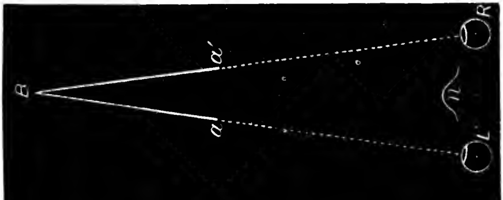


FIG. 79.

these figures therefore truly represent the position of the double images (as indeed they do), then they do not represent the *visual* or *apparent* position of the *visual lines*. The truth is, in natural vision *the visual* *lines are shifted*, as well as the images of all objects not situated at the point of sight, and to the same degree, *so that the position of such objects relative to the visual lines is perfectly maintained in the visual result.*

It is evident then that figures constructed on the usual plan, while they give correctly the place and distance of objects seen single, fail utterly to give the place of double images. They are well adapted to express binocular combination of similar objects or similar figures on the plane of sight, but are wholly inadequate to the expression of the facts of binocular perspective, whether in natural objects or scenes or in stereoscopic pictures.

In an article published in January, 1871,* I proposed, therefore, a new and I am convinced a far truer mode of diagrammatic representation of the phenomena of binocular vision, applicable alike to all cases. I am satisfied that if this method had always been used, much of the confusion and many of the mistakes to be found in the writings on binocular vision would have been avoided. But it is evident that such a new and truer method must be founded upon some fundamental binocular phenomena usually overlooked. I must first therefore enforce these. They may be compendiously stated in the form of *two fundamental laws.* It will be best, however, before formulating them, to give some familiar experiments, and then to give the laws as an induction from the facts thus brought out.

Experiment 1.—If a single object, as for example a finger, be held before the eyes in the median plane, and the eyes be directed to a distant point so that their axes are parallel, the object will of course be seen double, the heteronymous images being separated from each

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* "American Journal of Science," Series III, vol. i, p. 33.

other by a space *exactly equal to the interocular space.* Now, *the nose is no exception to this law.* The nose is always seen double and bounding the common field of view on either side.

Experiment 2.—If two similar objects be placed before the eyes in the horizontal plane of sight, and separated by a space exactly equal to the interocular space, and the eyes be directed to a distant point so that their axes are parallel and the two visual lines shall pass through the two objects, then both objects will be doubled, the double images of each being separated by an interocular space; and therefore two of the four images—viz., the right-eye image of the right object, and the left-eye image of the left object—will combine to form a *single binocular image in the middle;* while the right-eye image of the left object will be seen to the left, and the left-eye image of the right object to the right. Thus there will be three images seen—a middle binocular image, and two monocular images, one on each side, that on the right side belonging to the left eye alone, and that on the left to the right eye alone. Now, *the eyes themselves are no exception to this law.* In binocular vision the eyes themselves seem each to double—two of the images combining to form *a binocular eye in the middle* (*œil cyclopienne*), while the other two are beyond the two images of the nose on either side. Each eye seems to itself to occupy a central position, while it sees (or would see if the nose were not in the way) its fellow on the other side of the double images of the nose.

In other words, in binocular vision, when the optic axes are parallel, as in gazing on a distant object, the whole field of view, with all its objects, including the parts of the face, is shifted by the right eye a half interocular space to the left, and by the left eye a half interocular space to the right, without altering the relative position of parts. It is evident that, by this shifting in opposite directions, the two eyes with their visual lines are brought together in perfect coincidence, so that corresponding points in the two retinæ seem to be perfectly united.

FIG. 80.

FIG. 81.

The facts as thus far stated—both the *actual condition of things* as we *know* them, and the *visual results* as they *seem* to the binocular observer—are represented in the following diagrams. Fig. 80 shows the actual condition of things, and Fig. 81 the visual result, in the first experiment; Fig. 82 the actual condition of things, and Fig. 83 the binocular visual result, in the second experiment. To explain further: In Fig. 80, *R* and *L* are the right and left eyes; *N*, the nose; *A*, the object in the median plane; the dotted lines *v v*, the direction of the visual lines. Fig. 81 represents the visual results; *E* being the combined or binocular eye (*œil cyclopienne*); *n* and *n′*, the two images of the nose belonging to the right and left eyes respectively; *V*, the combined or binocular visual line, looking between the double images *a* and *a′* of the object *A;* while *r′* is the position of the right eye as it would be seen by the left eye, and *l* of the left eye as it would be seen by the right, if the nose were not in the way, and *v* and *v′* are the positions of their visual lines if they were visible lines. Fig. 82 represents the actual condition of things when two similar objects *A* and *B* are before the eyes in the visual lines *v v;* and Fig. 83 is the visual result, in which *a′* and *b* are the monocular images, one belonging to the left and the other to the right eye, *AB* the combined

FIG. 82.

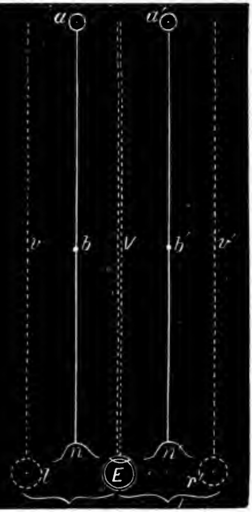
FIG. 83.

or binocular image, and the other letters representing the same as before.

Experiment 3.—These facts are brought out still more clearly if, instead of an object like *A*, Fig. 80, we use a continuous line or rod, as in Fig. 76. We have seen above that, with the optic axes parallel, any object placed in the median line of sight, at whatever distance, is separated into two images an interocular space apart.

Fig. 84.

Fig. 85.



Evidently, therefore, *the median line of sight itself is doubled*, and becomes two lines, which, resting on the nose on each side, run out parallel to each other indefinitely. Between these two lines the binocular eye (combined eyes) looks out along the combined visual line at a distant object. If the median *line* be occupied by a *real* visible line or a rod, we shall see two parallel lines or rods. If the median *plane* be occupied by a *real* plane, we shall see two parallel planes bounding the binocular field of view on each side, between which we look.

These facts are represented by the diagrams Figs. 84 and 85. In Fig. 84, *B* represents a rod resting on the root of the nose *n*, and held in place by the point of the finger *A*; *R* and *L* are the two eyes, and *v* and *v* the two visual lines in a parallel position. Such is the actual condition of things. Now Fig. 85 represents the visual results. It is seen that the nose *n*, the rod *B*, and the finger-point *A* of fig. 84 are all doubled, as *n n′*, *b b′*, *a a′* of fig. 85; while the two eyes, *R* and *L*, and the two visual lines, *v* and *v*, of fig. 84, are combined in the middle as the binocular eye *E*, which looks out along the combined visual line *V* between the parallel rods *b b′*, of fig 85.

As already stated, if instead of a rod we use a plane coincident with the median plane, then the plane is doubled, and we look between the doubled images. This is the case in using the stereoscope. The median plane of the stereoscope is doubled, and between its two images we look out on the combined pictures.

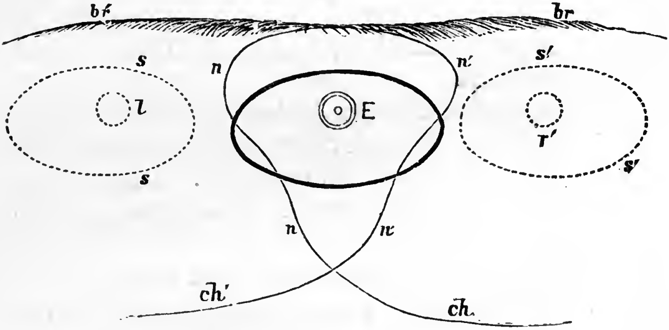
Experiment 4.—An excellent illustration of the fundamental fact, that in binocular vision the two eyes are moved to the middle and combined into a binocular eye, must be familiar to every one who has ever worn spectacles. If the spectacles are properly chosen, so that the distance between the centers of the two glasses is exactly equal to the interocular space, then we see but *one* glass exactly in the middle, through which the binocular eye seems to look. We would see two other glasses, monocular images, right and left, if these were not hidden by the nose. We do indeed see two others in these positions if we remove the spectacles to such distance that the nose no longer conceals them, while we still look through the middle glass at a distant object.

Many other familiar illustrations may be given. If we put our face against a mirror, so that forehead and nose shall touch the glass, and then gaze on vacancy, there will be of course four images of the two eyes in the mirror. Two of these, viz., the right-eye image of the right eye and the left-eye image of the left eye, will unite to form a central binocular eye, an image of our own central binocular eye, and into which our own seems to gaze. The nose will be seen double and on each side of the central eye, and beyond the double images of the nose on either side will be seen monocular images of the eyes. In other words, we actually see exactly what I have expressed in the diagrams (Figs. 83 and 85) representing visual results.

If, in place of the reflection of our *own* face in a mirror, we make use in this experiment of the face of another person, placing forehead against forehead, nose against nose, and the eyes exactly opposite each other, and gaze on vacancy, the same visual result will follow. Our own central binocular eye looks between our two noses into another central binocular eye, situated also between two noses. Other monocular eyes are seen beyond the noses, right and left.

The fields of view of the two eyes are bordered by the nose, the brows, and the cheeks. Its form therefore varies in different persons. It has no definite limit on the outside. I reproduce as Fig. 86 the diagram already used on page 91, representing rudely the general character of the field of view of the binocular observer. I have introduced the *œil cyclopienne* and the two monocular images of the eyes; and, in order to make it more comprehensible, I have supposed the observer to wear glasses. In this diagram, *n n* is an outline of the nose, *br* of the brow, and *ch* of the cheek of the right-eye field; *br′*, *n′ n′*, and *ch′*, the outline of the left-eye field. The middle space where they overlap, bounded on each side by the outline of the nose, *n n*, *n′ n′*, is the common or binocular field occupied by the central binocular eye *E*, surrounded by the single ellipse of the combined spectacle-glasses. I have also introduced in dotted outline the left eye *l* and the spectacle-rim *s s* as they would be seen by the right eye, and the right eye *r′* and spectacle-rim *s′ s′* as they would be seen by the left eye, if the nose were not in the way.

FIG. 86.



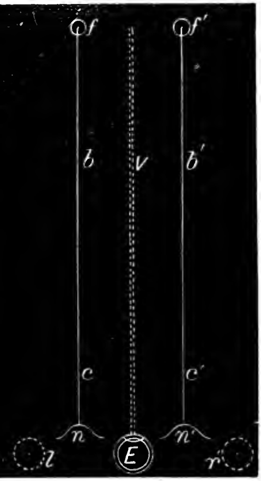
First Law.—We are now in position to formulate the first law. I would express it thus: In binocular vision, with the optic axes parallel, as in looking at a distant object, the whole field of view and all objects in the field, including the visible parts of the face, are shifted by the right eye a half interocular space to the left, and by the left eye the same distance to the right, without altering the relative positions of parts; so that the two eyes with their two visual lines seem to unite to form a single middle binocular eye, and a single middle visual line, along which the eye seems to look. It follows that any line, rod, or plane in the median line, as also the nose itself, is doubled heteronymously, and becomes two lines, rods, or planes, parallel to each other, and separated by a space exactly equal to the interocular space. Between the two noses, and between the two parallel lines, rods, or planes, the binocular eye seems to look out along the middle visual line upon the distant object. Of course, by this shifting of the two fields in opposite directions, all objects in the field are similarly doubled.

Thus in binocular vision the two eyes seem *actually* to be brought together and superposed, and corresponding points of the two retinæ to coincide. The two eyes become actually one instrument. And conversely, this apparent combination of two eyes and their visual lines is a necessary consequence of the law of corresponding points. For images on corresponding points are seen single; all objects on the two visual lines must impress corresponding points, viz., the central spots; therefore the visual lines themselves, if they were visible lines, would be seen single. But where could they be seen single except in the middle? Therefore the two visual lines must combine to form a single middle visual line.

We will next give experiments leading up to the second law. For this purpose let us recur to the experiment with the rod represented by Fig. 84. We reproduce this as Fig. 87, in order to compare with it the results of subsequent experiments. As already explained, if the rod *B* be placed in the median plane with the nearer end resting on the nose-root *n*, and the farther end held in place by the point of the finger *A*, the eyes looking at a distant object, as shown in Fig. 87, which represents the actual condition of things, then

Fig. 87.

Fig. 88.



the rod, together with nose and finger-point, will be doubled heteronymously and become two parallel rods,

Fig. 89.

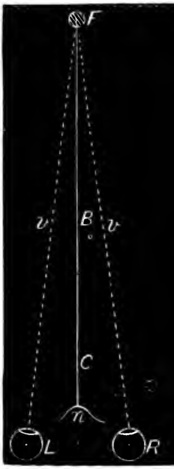
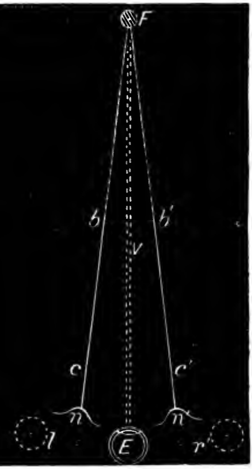


Fig. 90.



between which the binocular eye will look out along the binocular visual line at the distant object, as shown in Fig. 88, which represents the visual result.

Experiment 1.—Now, while we hold the rod in the position represented by Fig. 87, instead of looking at a distant object with eyes parallel, let the eyes be *converged* on the finger-point *F*, so that Fig. 89 shall represent the actual condition of things. We will observe that the double images of the rod represented in the visual result, Fig. 88, approach at their farther end, carrying all objects in the field with them, until they unite at the point of sight *F*, and we have the visual result represented in Fig. 90.

Fig. 91.

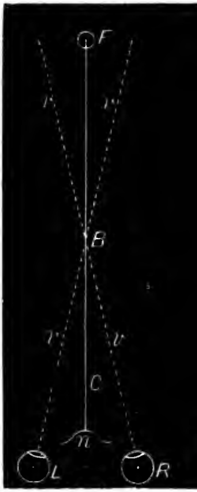
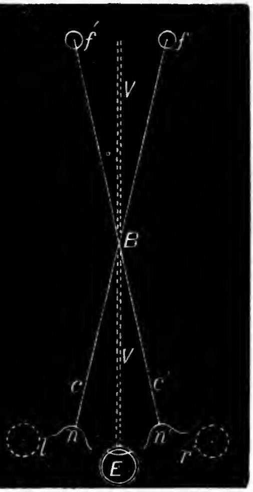


Fig. 92.



Experiment 2.—If by greater convergence we next look at some nearer point *B* on the rod, as in Fig. 91, which represents the actual relation of parts, then Fig. 92 represents the visual result. By comparing this with

the previous visual results, Figs. 88 and 90, it will be seen that the double images *b b′* approach each other until they unite at the point of sight, and the two images of the rod cross each other at this point, and therefore become again double beyond, but now homonymously. If by still greater convergence we look at a still nearer point *C*, Fig. 93, then the double images of the median rod, Figs. 87, 89, 91, will cross at the point of sight *C*, and give the visual result shown in Fig. 94.

Fig. 93.

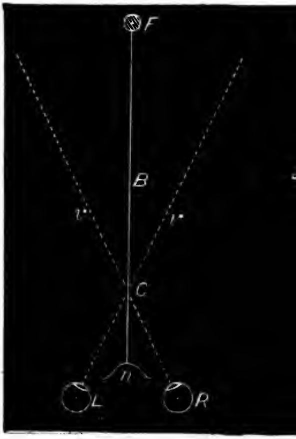
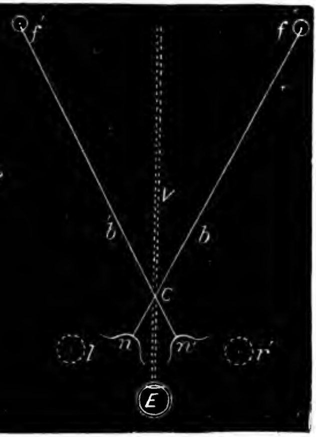


Fig. 94.



Finally, if the point of sight by extreme convergence be brought to the root of the nose, then the double images of the nose *n n′*, Figs. 92, 94, will be brought in contact, and the common or binocular field will be obliterated. In all cases it will be observed that the combined eyes look along the combined visual lines through the point of sight, and onward to infinite distance.

It is evident, then, that in optic convergence, as the two real eyes turn in opposite directions on their optic centers, the two fields of view turn also on the center of the binocular eye in directions opposite to the real eyes, and therefore to each other.

It will be observed that in speaking of visual phenomena I have used much the same language as other writers on this subject, and used also a somewhat similar mode of representation; only I have substituted eyes in the place of the nose, and put noses in the position of the eyes. I have made median lines cross each other at the point of sight, instead of visual lines, and visual lines combine in the middle as a true median visual line. In other words, I have used the true language of binocular vision. I have expressed what we *see*, rather than what we *know*—the language of simple appearance, rather than that mixture of appearance and reality which forms the usual language of writers on this subject.

Second Law.—The second law may therefore be stated thus: In turning the eyes in different directions without altering their convergence, *objects* seem *stationary*, and the *visual lines* seem to *move* and sweep over them; but when we turn the eyes in opposite directions, as in increasing or decreasing their convergence, then the visual lines seem stationary (i. e., we seem to look in the same direction straight forward), and all objects, or rather their images, seem to move in directions contrary to the actual motion of the eyes. The whole fields of view of both eyes seem to rotate about a middle optic center, in a direction contrary to the motion of the corresponding eyes, and therefore to each other. This is plainly seen by voluntarily and strongly converging the eyes on an imaginary very near point, as for example the root of the nose, and at the same time watching the motion of the images of more distant objects. The whole field of view of the right eye, carrying all its images with it, seems to rotate to the right, and of the left eye to the left—i. e., homonymously. The images of all objects, as they are swept successively by the two visual lines, are brought from opposite directions to the front and superposed. As we relax the convergence, and the eyes move back to a parallel condition, the two fields with their images are seen to rotate in the other direction—i. e, heteronymously. If we could turn the eyes outward, the two fields and their images would continue to rotate heteronymously. This, which we can not do by voluntary effort of the ocular muscles, may be done by pressing the fingers in the external corners of the two eyes. By pressing in the internal corners, on the contrary, the eyes are made to converge, and homonymous rotation of the fields of view is produced.

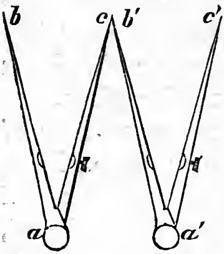
Or the law may be more briefly formulated thus: *In convergence and divergence of the eyes, the two fields of view rotate in opposite directions, homonymously in the former case and heteronymously in the latter, about the optic center of the binocular eye* (*œil cyclopienne*), *while the middle or binocular visual line maintains always its position in the median plane.*

Thus, then, there are two apparent movements of the visual fields accomplished in binocular vision. First, there is a shifting of each field heteronymously a half interocular space. This is involuntary and habitual, and would of itself double all objects heteronymously, separating their images exactly an interocular space. Second, in convergence, there is a rotation of each field about the optic center of the *œil cyclopienne* (or about an axis passing through that center and normal to the visual plane), homonymously. The necessary consequences of these movements are: (*a*) that the images of an object at the point of sight are superposed and the object is seen single, while objects on this side of the point of sight are doubled heteronymously, and those beyond the point of sight homonymously; (*b*) that all objects (different objects) lying in the direction of the two visual lines, whether nearer than or beyond the point of sight, have their images (one of each) brought to the front and superposed; so that the two visual lines are under all circumstances brought together and combined to form a single binocular visual line, passing from the middle binocular eye through the point of sight and onward to infinity.

In all the experiments which follow on this subject it is necessary to get the interocular space with exactness. This may be done very easily in the following manner:

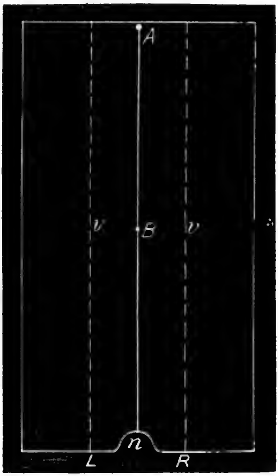
Experiment.—Take a pair of dividers and hold it at arm's length against the sky or a bright cloud, and, while gazing steadily at the sky or cloud, separate the points until two of the four double images of the points shall unite perfectly, as in Fig. 95. The distance between the points of the dividers, equal to a–a', or b–b', or c–c', is exactly the interocular distance—i. e., the distance between the central points of the central spots of the two retinæ. The only difficulty in the way of perfect exactness in this experiment is the want of fine definition of the points when the eyes are adjusted for distant vision. This may be obviated by using slightly convex spectacles. The accuracy of the determination may be

Fig. 95.



verified thus: Measure the distance just determined accurately on a card, and pierce the card at the two points with small pin-holes. Now place the card against the forehead and nose, with the holes exactly in front of the two eyes, and gaze through them at a distant horizon or cloud. If the measurement is exact, the two pin-holes will appear as one; their coincidence will be perfect. As thus determined, I find my interocular space almost exactly 2½ inches (63.5 mm.). It will be seen that this method is founded upon the opposite shifting of the two fields of view half an interocular space each, spoken of in the first law. The two pin-holes are seen as one *exactly in the middle*, which is looked through by the *œil cyclopienne;* and this is therefore one of the very best illustrations of such shifting of the two eyes and their visual lines to the middle.

FIG. 96.



We will now give some additional experiments illustrating and enforcing these two laws, and showing the absolute necessity of using this new mode of diagrammatic representation in all cases in which binocular perspective is involved. For this purpose I find it most convenient to use a small rectangular blackboard about 18 inches long and 10 inches wide, Fig. 96. Mark two points *R* and *L* at one end, with a space between exactly equal to the interocular space, and in the middle between these points make a notch *n* in the edge of the board to fit over the bridge of the nose. Such a board is admirably fitted for all experiments on binocular perspective.

Experiment 1.—Draw a line through the middle of the board from the notch *n*, Fig. 96. This will be the visible representative of the median line; and as the median line is used in all the experiments, this may be made permanent. On this line place two pins at *A* and *B*. Draw also from the points *L* and *R* dotted lines

FIG. 97.

FIG. 98.

parallel to the median line and to each other, as the visible representatives of the visual lines when the optic axes are parallel, as when looking at a distant object. Now fit the plane over the bridge of the nose, and place it in a horizontal position a little below the primary plane of vision, say half an inch or an inch, so that the whole surface is distinctly seen, and then look beyond at a distant object. Leaving out the board in the representations, the actual position of the lines is shown in Fig. 97 and the visual result in Fig. 98. Remembering that in all our figures capitals represent combined or binocular images, simple italics right-eye images, and primed italics left-eye images, it will be seen that the whole board, with all the lines and objects on it and the parts of the face, has been shifted left and right by the two eyes, so that the nose and the median line are seen as two noses and two parallel lines with their pins, separated by a space exactly equal to the interocular space, and the two visual lines are brought together and united in the middle to form a common visual line *V*, as if coming from a single binocular eye *E*. If two small circles be drawn or a pin be set at the end of the dotted visual lines in Fig. 97, these will be united in the result Fig. 98, at the end of the combined visual line *V*. There will also of course be seen to the extreme right and left monocular images of the dotted representatives of the visual lines, and of the circles or pins at their farther end. I have connected by vincula the images of the whole drawing, the primed vinculum being the image of the left eye, the other of the right.

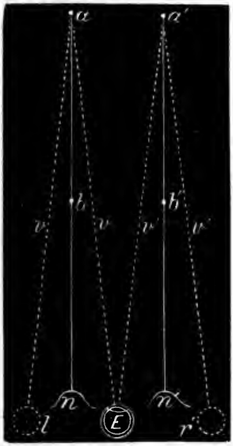
Experiment 2.—If we now erase the parallel visual lines *v v* on the board, and draw them convergent on the pin *A*, so that Fig. 99 shall represent the actual condition, and then adjust the board again to the nose and look at the pin *A*, the visual result, or what we shall see, is given in Fig. 100. By comparing this result with the actual condition of things—i. e., by comparing Fig. 100 with Fig. 99—it would seem as if the whole drawing on the board, including the eyes and nose, had been turned about the point of sight *A* by the two eyes in opposite directions, the right carrying it to the position *l A E*, the left eye to the position *r′ A E*, shown by the unprimed and the primed vinculum respectively.

Fig. 99.

Fig. 100.

The *real* nature of the rotation, however, is shown by comparing the appearance of the drawing when the eyes are parallel with its appearance when the eyes are converged on *A*. Fig. 101 represents the visual result when the same drawing is viewed with the eyes parallel. By comparing this figure with the visual result when the eyes converge on *A* (Fig. 100), it is seen that the two images of the whole drawing rotate on the optic center of the binocular eye *E*, until the pins *a a′* and the visual lines *v v′* of Fig. 101 unite to form the binocular image *A* and the binocular visual line *V* of Fig. 100. If the eyes be converged very gradually, the slow approach of the points *a a′*, carrying with them the dotted lines *v v′*, as if turning on the center of the binocular eye *E*, can be distinctly seen.

FIG. 101.

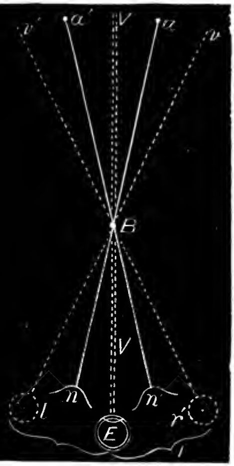


Experiment 3.—If we again erase the dotted representatives of the visual lines and draw them converging and crossing at the nearer pin *B*, as in Fig. 102, then Fig. 103 gives the visual result. It is as if the whole diagram, Fig. 102, had been rotated on the point of sight *B* in two directions, viz., a right-handed rotation by the right eye and a left-handed rotation by the left eye. But what actually takes place is seen by first gazing at a distant object and comparing the visual result thus obtained, shown in Fig. 104, with that obtained by converging the eyes on *B*, shown in Fig. 103. It is seen that the double images of the whole diagram turn on the center *E* until *b b′*, Fig. 104, unite to form *B*, Fig. 103, and *v E*, *v′ E* to form *V E;* and of course the other lines, *a a′*, *v v′*, cross over and become homonymous. When the eyes converge as in this last experiment, the points *R* and *L* on the experimental board, Fig. 96, must be a little less than an interocular space apart.

Let us now return to the original experiment with three points or objects in the median line given on page 213. We reproduce here the figure (Fig. 105) usually used to illustrate the visual result. We have already shown how impossible it is to represent all the visual results in this way. If we are bent on representing the parallactic position of the double images, then we must refer them all to the same plane, as in Fig. 105; but this is false. If, on the other hand, we try to place

Fig. 102.

Fig. 103.



them at the distances at which we actually see them, observing the law of direction, then the double images unite, which is also false.

Fig. 104.

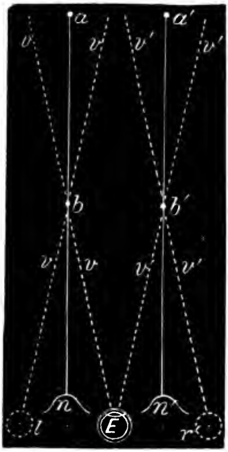
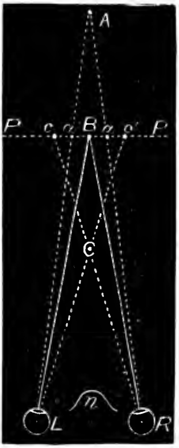


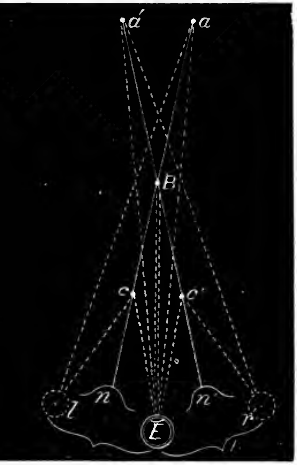
Fig. 105.



Experiment 4.—Now try the same experiment by the use of the board, and the true mode of representation becomes manifest. On the median line, Fig. 106, place three pins, and draw dotted lines to each of them from the position of the eyes, which shall be the visible representatives of either visual lines or ray-lines. As in the experiment the eyes will look at *B*, let the dotted lines to *B* be stronger to represent visual lines; then the others will represent only ray-lines. Now when this diagram is observed with the point of sight at *B*, Fig. 106, then the *visual result*—i. e., what we actually see on the board—will be Fig. 107. It is seen that the whole diagram Fig. 106 is rotated in opposite directions about the point of sight *B* to make the result, Fig. 107. But the real nature of the rotation is shown by comparing the result with the eyes parallel, Fig. 108, with the result with the eyes converged on *B*, Fig. 107.

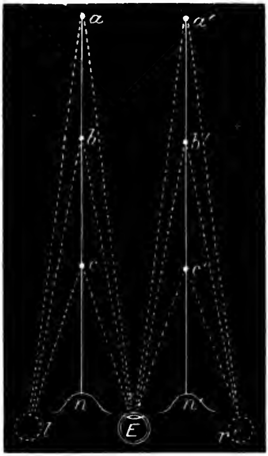
FIG. 106.

FIG. 107.



With the eyes parallel, the whole diagram is simply doubled heteronymously by each eye shifting it half an interocular space in opposite directions. Now converging the eyes slowly, the two images of Fig. 106 shown in Fig. 108 are seen to rotate on *E* until the points *b b′* and the dotted lines *b E*, *b′ E* unite to form *B E*, Fig. 107. In doing so, *c c′* have approached, but not united; they are therefore still heteronymous, while *a a′* have met and passed each other, and become homonymously double.

Fig. 108.



Therefore Fig. 107 truly represents all the visual facts. It gives both the parallactic position of the points in relation to the observer, their relative position in regard to each other, and their relative distance. Or, if we leave out in the original diagram, as complicating the figure, all except the necessary median line and pins, as in Fig. 109, then the visual result is given in Fig. 110. Or, adding in the visual result only the visual line and the most necessary ray-lines, viz., those going to the binocular eye, we have Fig. 111. This last figure we shall hereafter use to represent the phenomena of binocular perspective.

Application to Stereoscopic Phenomena.—We wish now to apply this new method of representation to the phenomena of the stereoscope. We reproduce here as Fig. 112 the diagram used on page 131. It is seen that while the different distances, *A* and *B*, at which the foreground and background are seen, are truly represented, no attempt is made to represent the double images of the foreground when the background is regarded, or *vice versa.* It is impossible by this usual method to represent these double images without referring them to the same plane; but this would of course destroy the perspective, which it is the very object of the diagram to illustrate. The new method, on the contrary, represents the true distance of the point of sight, and the true positions and distances of the double images, and therefore the true binocular perspective. In other words, it represents truly all the binocular visual phenomena. It will be best to preface this explanation by an additional experiment.

FIG. 109.

FIG. 110.

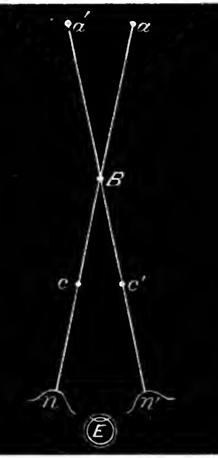
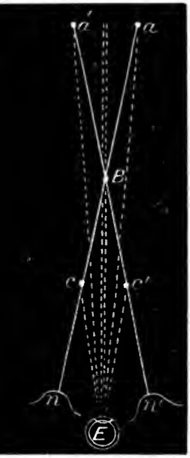


FIG. 111.



Experiment.—If a rectangular card, like an ordinary stereoscopic card, or a letter envelope, be held before the face at any convenient distance while the eyes gaze on vacancy, i. e., with the optic axes parallel, the two images of the card will be seen to slide over each other heteronymously, each a distance equal to a half interocular space, and therefore relatively to each other exactly an interocular space. If the card be longer than an interocular space, there will be a part where the two images will overlap.

Fig. 112.

This is represented in the accompanying diagrams, of which Fig. 113 represents the card when looked at, and Fig. 114 the visual result when the eyes are parallel. In this visual result *c c* is the right-eye image of the card, *c′ c′* the left-eye image, and *d d* the binocular overlapping. This overlapped part will be opaque, because nothing can be seen behind it by either eye. But right and left of this are two transparent spaces. That on the left belongs to the image of the right eye, but not to that of the left, and therefore the left eye sees objects beyond it. That on the right belongs to the left eye, but the right eye sees objects beyond it.

If two circles, *a a*, be drawn on the card, Fig. 113, an interocular space apart, they will unite into a binocular circle *A* in the center of the opaque part, Fig. 114; while two monocular circles *a a′* will occupy the transparent borders.

Fig. 113.

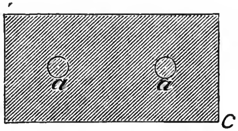
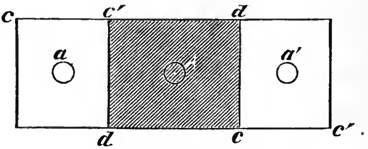


Fig. 114.



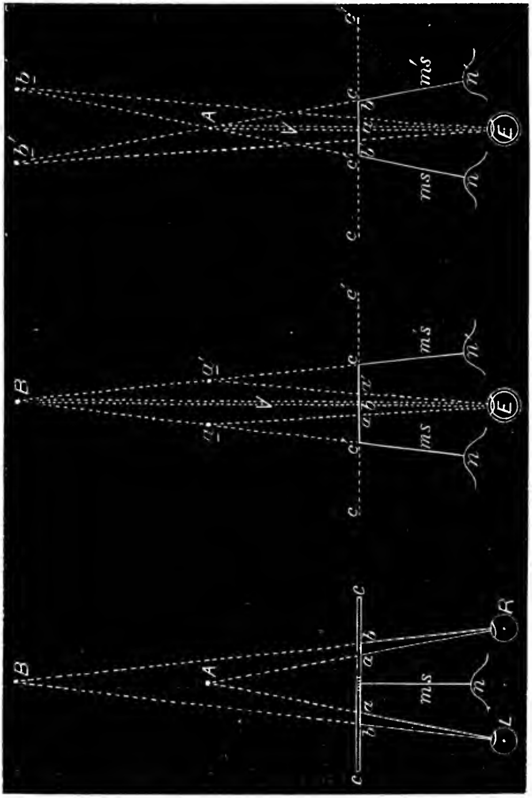
By the law of alternation spoken of on page 93, sometimes the right eye will prevail, the right-hand transparent border will disappear, and the whole right-eye image *c c* will appear opaque. Then the left eye prevails, and the left-hand border will disappear, and the whole left-eye image *c′ c′* will appear opaque. Sometimes both borders disappear, and only the binocular overlapping is seen. Sometimes the whole double image, including both borders, becomes opaque. But the true normal binocular appearance or visual result is given in Fig. 114—i. e., opaque center and transparent borders, these borders being exactly equal to the interocular space.

We are now prepared to show how stereoscopic phenomena may be represented by our new method. In Fig. 115, *c c* represents a stereoscopic card in position; *m s*, the median screen, which cuts off the supernumerary monocular images; *a a*, identical points in the foreground of the pictures, and *b b*, in the background. The two eyes and the nose are represented as before by *R*, *L*, and *n;* and *a R*, *a L*, *b R*, *b L* are ray-lines. Leaving out the dotted lines beyond the card, this diagram represents the actual condition of things. The dotted lines beyond the picture show the mode of representation usually adopted. When the eyes are directed to *a a*, then *a R*, *a L* become visual lines, and *a a* are united and seen at the point of sight *A*. When the eyes are directed to *b b*, then *b R*, *b L* become visual lines, and *b* and *b* are united and seen single at the point of sight *B*.

The defect of this mode of representation is, that it takes no cognizance of the double images of *b b* when *A* is regarded, or of *a a* when *B* is regarded. The attempt to represent these would destroy the perspective.

By our new method, on the contrary, all the phenomena are represented. In Fig. 116 is shown the visual result when the eyes are fixed on the background; in Fig. 117, the visual result when the eyes are fixed

Fig. 115. Fig. 116 Fig. 117.



on the foreground. In Fig. 116 we see that the nose *n n′* and the median screen *ms m′s* are doubled heteronymously, and the space between the two is the common and only field of view (for the monocular fields are cut off by the screen). In the middle between these is the binocular eye *E*, looking straight forward. This is manifestly exactly what we see in the stereoscope. Again, we see that the two images of the card have slidden over each other, in such wise that *b b*, Fig. 115, are brought together in the middle, united, and seen single in Fig. 116. But where? at what distance? Evidently this can only be at the point of sight, which, as I have already explained, is, in diagrammatic representations of visual phenomena, where the common visual line and the two median lines meet one another at the point *B*, Fig. 116. Meanwhile *a a*, Fig. 115, will have crossed over and become heteronymous, and their double images *a a′*, Fig. 116, will be seen just where their ray-lines *E a* and *E a′* cut the median planes, viz., at $\underline{a}\ \underline{a}'$. In Fig. 117, which is the visual result when the eyes are fixed on the foreground, the shifting or sliding of the two images of the card is not quite so great as before. It is only enough to bring together the nearer points *a a*, Fig. 115, but not *b b*. These latter, therefore, are homonymously double. The united images of *a a* are seen single on the common visual line, and at the distance *A* where the double images of the median line cross each other; while *b b* are seen homonymously double, and at $\underline{b}\ \underline{b}'$, the intersection of their ray-lines with the continuation of the median lines after crossing; for homonymous images are always referred *beyond* the point of sight.

The mode of representing combinations with the naked eyes by squinting is similar. Of course the place of the combined picture will in this case be between the eyes and the card. I reproduce (Fig. 118), for the sake of comparison, the usual mode of representation from page 139. In order to make the perspective natural, it is necessary, as already explained, to reverse the mounting. In Fig. 118 the mounting is thus reversed, as seen by the fact that points in the foreground, *a a*, are farther apart than in the background, *b b*. The usual mode of representation is shown in this figure. The true visual result is shown in Figs. 119 and 120, of which Fig. 119 represents the result when the observer is regarding the background, and Fig. 120 when he is regarding the foreground. It is seen that not

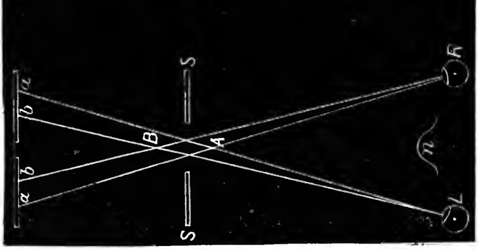


Fig. 118.

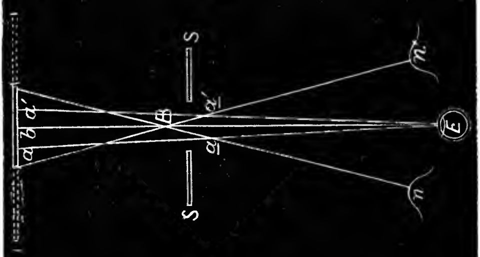


Fig. 119.

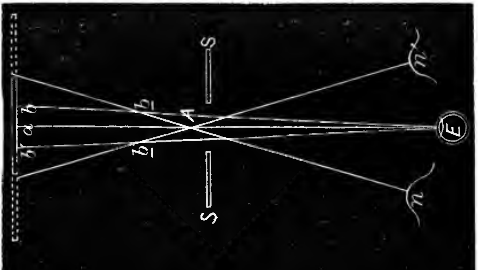


Fig. 120.

only does the diagram give truly the place and distance of the combined image, but also of the double images by means of which perspective is perceived.

It will be remembered that double images may be nearer or farther off than the point of sight, but that in the former case they are heteronymous, in the latter homonymous. In this way we at once perceive their distance in relation to point of sight. Now, in the new mode of representation, this fact is also indicated. In both of the figures 119 and 120 there are two places where the ray-lines cut the median lines, and therefore where double images may be formed; but in the one case the images are heteronymous, and therefore we refer them to the nearer points *a a′*; in the other case they are homonymous, and therefore we refer them to the farther points *b b′*.

If stereoscopic pictures mounted in the usual way be combined with the naked eyes by squinting, or pictures with reverse mounting be combined in the stereoscope, the perspective will be inverted. In this case the diagrammatic representation is exactly the same, except that the double images of points in the foreground *a a′* will now be homonymous, and therefore referred to the other possible point of reference, viz., beyond the point of sight; and double images of points in the background *b b′* will become heteronymous, and therefore referred to the nearer point.

Some curious Phenomena illustrating the heteronymous Shifting of the two Fields of View.

Experiment 1.—To trace a picture where it is not. Take a postage stamp, or a piece of coin, or a medallion, or a small object or picture of any kind; place it on a sheet of white paper. Take then a thin opaque screen, like a pamphlet, or thin book, or piece of cardboard, and set it upright on the *right side* of the object or picture, and bring down the face upon the top edge of the screen, in such wise that the latter shall occupy the median plane. If we now gaze with the eyes parallel—i. e., on vacancy—the median card will double and become two parallel cards, and in the middle between them will be seen the object or picture. With a pencil in the right hand we may now trace the outline of the object or picture, by means of its image, on the right side of the screen, although the actual object or picture is on the left side of the same.

The accompanying diagrams illustrate and explain the phenomena. In Fig. 121, *R* and *L* are the two eyes looking *down* on the paper sheet *sh; ms* is the median screen, and *c* the coin on its *left side; a*, the spot where the outline is traced with the pencil *P*. This

FIG. 121.

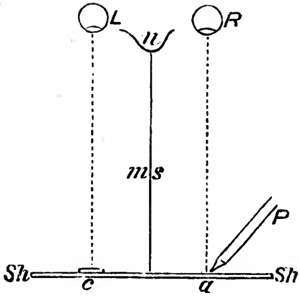


FIG. 122.

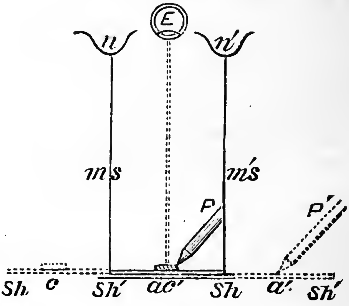
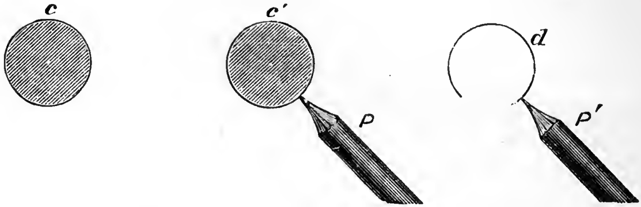


figure therefore gives the actual condition of things. The visual result, and therefore the explanation, is given in Fig. 122. By careful inspection it is seen that the screen is doubled heteronymously, and becomes two parallel screens *ms*, *m′s;* that the two images of the paper sheet are slidden over each other, so that the left eye, its visual line, and its image of the coin *c* are all brought to the middle, while the right eye, its visual line, and its image of the pencil and of the point *a* are also brought to the middle from the other side, and superposed. We therefore see the image of the coin and trace its outline exactly an interocular space distant from its real position. If it were not for the screen, there would be another (right-eye) image of the coin and another (left-eye) image of the pencil and of the point *a*. These I have indicated in dotted outline.

Experiment 2.—If we make the experiment without the use of the median screen, then the cause of the phenomenon becomes obvious. If we lay a piece of money on a sheet of paper, and then gaze in the direction of the coin, but with the eyes parallel—i. e., on vacancy—the money of course separates into two images an interocular space apart. If we approach this with a pencil for the purpose of tracing the outline, we will see the pencil also doubled. If we now bring corresponding images in contact—i. e., right-eye image (left in position) of the pencil with the right-eye image (left in position) of the coin—we touch the coin with the pencil. But if, on the contrary, we bring the right-eye image (left in position) of the pencil to the left-eye image (right in position) of the coin, we may trace the outlines of the piece an interocular space distant from its true position. This is shown in Fig. 123, which gives the visual result of such an experiment—*c* and *c′* being the right- and left-eye images of the coin, and *P* and *P′* of the pencil. If, while the operation is going on, we observe carefully, we will see to the right the left-eye image of the pencil, *P′*, engaged in making a tracing. But there is no tracing in this place; it is only the left-eye image of the real tracing being made by the other pencil, P. In the previous experiment the screen cuts off all the images except the right-eye image of the pencil and the left-eye image of the coin, which are brought together in the middle.

Fig. 123.



Tolerably good tracings of a picture may be made in this way. The only difficulty in making them really accurate is the unsteadiness of the optic axes, and therefore of the place of the image. I have, however, used this method in making outline tracings of microscopic objects, which may be filled out afterward. For this purpose a card is placed on the right side of the microscope, and the microscopic object is viewed with the left eye, while the right eye is used for guiding the pencil. Precisely as in the experiment with the coin (Fig. 123), the left-eye image of the object and the right-eye image of the pencil and of a certain spot on the card are brought together in the middle.

Experiment 3.—To trace the outlines of a light on an opaque screen. The same experiment may be modified in an interesting way thus: Set a light in front of you on a table. Place a median screen of cardboard or of tin between the eyes, so that the light can be seen with both eyes. Now bend the screen to the right so as to make a right angle at the distance of 6 or 8 inches from the eyes. This part will cut off the view of the candle-flame from the right eye. Nevertheless, while gazing steadily at the flame, a really correct outline of it may be drawn on the opaque transverse screen, precisely as if it were transparent. This is illustrated and explained by the accompanying diagrams. Fig. 124 is the actual condition of things. *F* is the flame; *ms*, the median screen, resting on the nose *n*; *ts*, the transverse portion of the screen. Now, just where

FIG. 124.

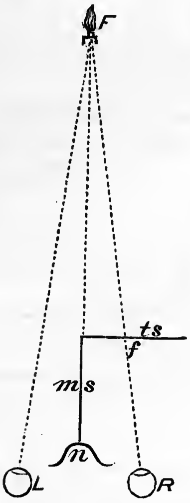
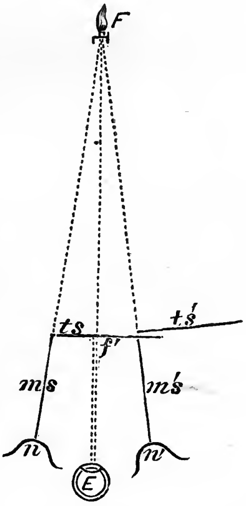


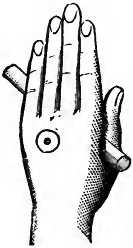
FIG. 125.



the visual line of the right eye pierces the transverse screen, viz., at *f*, we may draw the picture of the flame *F*, precisely as if it were transparent. The explanation is found by examining the visual result, Fig. 125. By the heteronymous doubling of the median and transverse screens, the left-eye image of the flame and the right-eye image of the transverse screen *ts* are brought together, and the flame may be seen as it were through the opaque screen as a transparency, and drawn at f'. In order to show that the flame is seen only by one eye, I have stopped one of the combined visual lines at the screen. The apparent transparency of an opaque screen in this case is precisely the same as the transparent borders of an opaque screen mentioned and explained on page 240.

Experiment 4.—To see through a book, a deal board, or the back of the hand, or even if necessary through a millstone. Roll up a thin pamphlet into a hard tube a half or three quarters of an inch in diameter, and hold it with the left hand between the thumb and hand, as shown in Fig. 126. Place the right eye to the end of the tube and look through the tube at the opposite wall, or still better at a map or picture hanging on the wall, while the back of the hand conceals the map or picture from the left eye. A circular spot on the wall or map will be seen through the center of the hand (Fig. 126), precisely as if there were a circular hole in the hand. Of course a book or an opaque plate of any kind may be substituted for the hand in this experiment.

FIG. 126.



The explanation is as follows: The visual line of the right eye passes through the axis of the tube and pierces the center of the circular visible area of the object regarded, while the visual line of the left eye pierces the back of the hand or the book at a point distant from the axis of the tube just an interocular space, or about $2\frac{1}{2}$ inches. By the right and left shifting of the fields of view already explained, the two visual lines are brought together in the middle; and therefore the center of the area regarded by the right eye and the spot on the hand or book pierced by the left visual line are also brought together and superposed.

One thing more to complete the explanation: The impression on the right eye prevails over that on the left — the impression of the circular area obliterates that of the corresponding area on the hand or book for two reasons: first, because the circular area is strongly differentiated from the rest of the right-eye field of view (i. e., the dark interior of the tube), while the corresponding or coincident area of the left-eye field (the hand or book) is not thus differentiated; and second, because both eyes are focally adjusted for the distance of the object seen by the right eye only. Thus it happens that the right eye sees only the circular area, the rest of its field being very dark; while the left eye sees all its field except the spot corresponding to and covering the circular area. Thus the binocular observer sees the general field of the left eye (the hand or book), in the middle of which he also sees the circular area of the right-eye field. But if an ink-spot be made on the back of the hand or book just where the left visual line pierces it, the impression of this will be strong enough to resist obliteration; the strongly differentiated ink-spot will be seen in the center of the circular area, as shown in Fig. 126.

CHAPTER IV.

VISUAL PHENOMENA IN OCULAR DIVERGENCE.

The only normal condition of the optic axes is either parallelism or convergence. We can not voluntarily make the optic axes divergent, because there is no useful purpose subserved by such a position; there would be no meeting of the optic axes, and therefore no point of sight. All the advantages of binocular vision are conditioned on convergence only. Divergence would only confuse by giving false information. But, although the power of divergence could be of no use and has therefore never been acquired, yet under certain circumstances divergence does occur, and the curious phenomena which then follow are an admirable illustration of the principles of binocular vision already set forth. We will give a few of these phenomena.

1. In Drowsiness.—It is well known that in extreme drowsiness, when we lose control over the ocular muscles, we see double images. It is universally believed and taught by physiologists that this is the result of *convergence* of the optic axes in sleep. I know of no observations purporting to prove this. It is probably an inference from the contracted state of the pupils in sleep, and the fact that contraction of the pupils is usually consensual with optic convergence.* This view is certainly false. Double images in sleepiness are certainly due to *divergence,* not convergence, of the optic axes.

In extreme drowsiness I have often observed the object which I was regarding (it might be the head of a dull speaker) divide into two images, which then separated more and more, until at a distance of 30 feet they were 10 to 15 feet apart. Even under these conditions I have found it possible to make a scientific experiment. Often, control over the ocular muscles is lost even while consciousness and control over mental acts is still perfect. Often, although by effort I could retain control over the eyes, I have chosen to abandon it in order to make the following experiments.

Experiment 1.—As soon as the images are well separated, I wink the *right* eye: immediately the *left* image disappears. The images are therefore *heteronymous.* But convergence produces homonymous images, while parallelism and, *a fortiori,* divergence produce heteronymous images. In this case the heteronymous images can not be produced by mere parallelism, because this state separates the images only an interocular space, or about 2½ inches, whereas the images may be separated many feet: therefore they are produced by *divergence.* The amount of divergence is easily calculated. At a distance of 30 feet a separation of the double images of 10 feet would require an angular divergence of the optic axes of nearly 19°; a separation of 15 feet would indicate an angular divergence of 28°.

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* "In sleep and in sleepiness both eyes are turned *inward* and upward." "The contracted state of the irides in sleep is a consensual motion dependent on the position of the eyes, which are turned inward and upward."—Müller, "Physiology," Am. ed., pp. 810 and 535.

In every such experiment the consciousness is quickly and completely aroused, and the double images are speedily reunited, though not so speedily but that the result is unmistakable. But, lest some may regard the speedy union of the images as an objection to this experiment, we will take another.

Experiment 2.—While lying abed in the morning, if one gazes on vacancy, objects near at hand (say the bedpost) are doubled heteronymously, the images being 2½ inches apart. If, while thus gazing and observing the heteronymous images, one should be overtaken by drowsiness and consequent loss of control over the ocular muscles, he will see that the already heteronymous images separate more and more. Now, if this were due to convergence, the heteronymous images would approach, unite, cross over, and become homonymous.

It is certain, then, that in myself, in extreme drowsiness, when control over the ocular muscles is lost, and therefore presumably in sleep, the eyes *diverge.* I have also satisfied myself that my case is not exceptional in this respect, for my results have been verified by several other persons. I think, therefore, I may assume it as a general law.

Double vision is also a well-known phenomenon of extreme intoxication. The unnatural appearance of the eyes in such cases is due to want of parallelism of the optic axes. I have on several occasions examined the eyes of those in this sad condition, and have always found the axes divergent. This seems to arise from partial paralysis of the ocular muscles.

If we examine the eye-sockets of a human skull, we find that their axes diverge about 25°–30°. This is about the extreme divergence of the optic axes in drowsiness. It is probable, therefore, that in a state of perfect relaxation or paralysis of the ocular muscles the optic axes coincide with the axes of the conical eye-sockets, and that it requires some degree of muscular contraction to bring the optic axes to a state of parallelism, and still more to one of convergence, as in every voluntary act of sight. In the human eye, therefore, and also in that of the highest animals, there are three conditions of the optic axes: first, convergence, as when we look at a near object; second, parallelism, as when we look at a distant object or gaze on vacancy; third, *divergence*, when we lose control over the ocular muscles, as in drowsiness, in drunkenness, in sleep, and in death. The first requires a distinct voluntary contraction of the ocular muscles; in the second there is no voluntary action, but only that involuntary tonic contraction characteristic of the healthy waking state; in the third the relaxation is complete. The first is the *active* state of the eye, the second the *waking* passive state, the third the absolutely passive state.

2. Other Modes of producing Divergence.—But the divergence of the optic axes may be effected in other ways. In most normal eyes the passive state is one of parallelism. It is easy therefore to double homonymously the images of an object at any distance by convergence, but most persons would find it impossible voluntarily to double the images of a very distant object, as for example a star, heteronymously—i. e., by divergence. Yet under certain conditions a slight divergence is possible. For example, I find I can (and I believe most persons can) combine with the naked eyes and with natural perspective (i. e., beyond the plane of the card) stereoscopic pictures in which identical points are farther apart than the interocular distance. I can

(7.11

not always succeed, being able to do so only when my mind is in an exceptionally passive state.

Experiment 3.—I take now a skeleton stereoscopic diagram, identical points in the background of which are separated by a space greater by an eighth of an inch than my interocular space. By holding it at arm's length so as to make the divergence as small as possible, I succeed in combining. After the combination is stable, I can bring the card nearer and nearer until it is within 5 inches of my eyes, and yet the combinaation is retained. But this corresponds to a divergence of only 1½°.

Experiment 4.—But by mechanical force we may make the eyes diverge 40° or 50°. This is done by pressure in the external corner of the eye. By thrusting a finger of each hand into the external corners of the eyes I can make the two images of an object directly in front separate 50°, or the images of two objects situated 25° to the right and left of the median line, and therefore 50° apart from each other, come to the front and unite.

The following diagrams represent and explain the visual phenomena in divergence of the optic axes.

In Fig. 127, which represents the actual relation of parts, *m* is the median line; *v v*, the visual lines or optic axes produced; *A*, an object on the median line; *b b*, two similar objects in the direction of the diverging visual lines; and *r r*, ray-lines from the object *A*. Fig. 128 shows the visual result if the lines in Fig. 127 were visible lines drawn on the plane described on page 231. It will be seen that by heteronymous shifting and then heteronymous rotation the whole diagram represented by Fig. 127 has been carried and rotated by the right eye to the position of the lines connected by the unprimed vinculum, and by the left eye to the position of the lines connected by the primed vinculum. By this means the two visual lines *v v* are brought together and combined as the common visual line *V*, and two of the images of the objects *b b* are brought together and superposed at *B*; the median line is doubled and rotated heteronymously to the positions *m m′*, carrying with them the double images of the median object *A* as *a a′*. The above diagram correctly represents the position and the distance of the double images *a a′*, and the *position* of the combined image *B*, but can not represent the *distance* of the combined image, *because there is no point of sight.* For the point of sight is *really* the point of optic convergence or *meeting of visual lines*; in *diagrams* representing visual results, it is the point *of crossing of the doubled median lines*; but this point, by both definitions, would be in this case behind the head. The diagram therefore correctly represents *all* the visual facts; for, there being in divergence

FIG. 127.

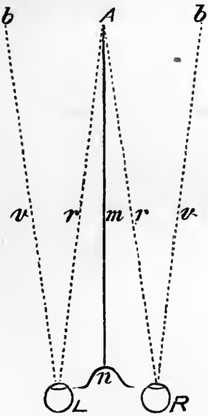
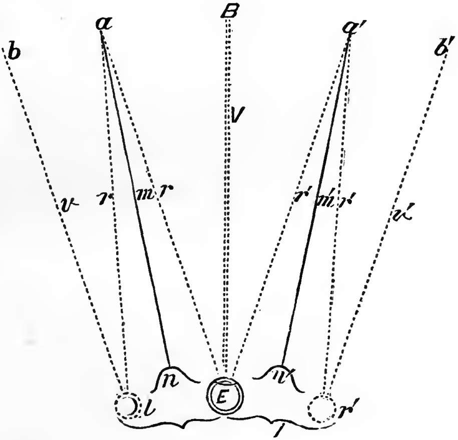


FIG. 128.



no point of sight, the distance of objects in the visual line is indeterminate as represented. It is impossible by the usual method to correctly represent *any* of the visual facts.

3. If the Law of Direction be opposed to the Law of Corresponding Points, the Latter will prevail.—These two most fundamental laws of vision are sometimes in discordance with each other. The reason of this may be thus explained: The law of direction is the fundamental law of monocular vision, as the law of corresponding points is of binocular vision. Now, for each eye, and therefore for the monocular observer, direction is determined by reference to the *optic axis*, but for the binocular observer by reference to the *median line*. On account of this difference of line of reference, while objects seen single are seen in their true positions, double images are always seen in positions different, and in some cases widely different, from the object which they represent. The difference may even amount to 45°. For example: The binocular field of view in my own case is 100° in a horizontal direction. By strong convergence I can nearly bring the double images of the root of my nose together, and thus obliterate the common field. I am sure therefore that I can make the optic axes of my two eyes cross each other at right angles. In such a case, of course, objects directly in front are doubled and their images separated 90° from each other, while objects lying to the right and left 90° from each other are brought to the front and their images superposed. Here the images are 45° from the true position of the objects which they represent. Thus, Fig. 129 represents the actual relation of things in this case, and Fig. 130 the visual result, showing that the positions of the objects *M* and *a a* are completely reversed. It may indeed be said that the case of *a a* seen in front may be reconciled with the law of direction. For, if the combined images be referred to the point of optic convergence *A*, as indeed they often are, then each eye sees its own object in its true direction, but only mistakes its distance. To this I would answer that *each eye* does indeed give the true direction, as is quickly shown by shutting one of them, but the *two eyes* together do not. Each sees its own object in

FIG. 129.

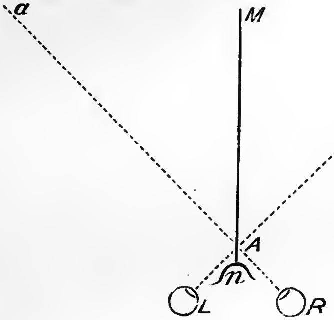
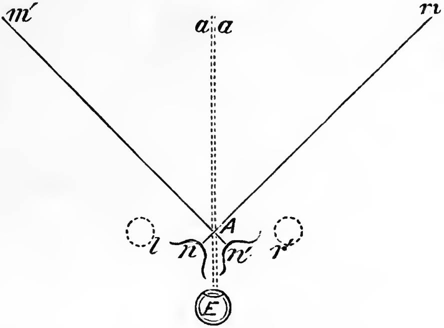


FIG. 130.



the true direction, but the *binocular observer* sees their combination in a wrong direction. In the case of the double images *m* and *m′* of the object *M*, it is still more difficult to explain their apparent position by the law of direction.

A curious Corollary.—It is seen that, under all circumstances, whatever be the position of the optic axes, objects in the visual lines are moved to the front and seen there. Now the same would be true if our eyes were turned directly outward right and left. There can be no doubt that if we could turn our eyes directly outward, or if our eyes, retaining their present organization and properties in regard to corresponding points, were transferred to the sides of the head with their axes straight right and left—i. e., making an angle of 180° with each other—*images of objects in the direction of these axes*, and therefore directly right and left, would be moved round 90° each, and combined and seen directly in front. This seems an extraordinary result, but it is a necessary consequence of the law of corresponding points. The retinal images of the two objects are on corresponding points, viz., on the central spots;

FIG. 131.

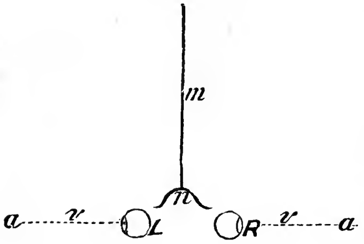
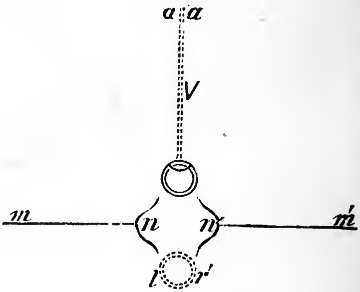


FIG. 132.



therefore, by the law of corresponding points, they must be seen as *one.* But where else can this take place but in front? The accompanying figures are a diagrammatic representation of these facts, Fig. 131 being the supposed condition of things, and Fig. 132 the visual result. After the frequent explanations of similar figures, a bare inspection will be sufficient.

CHAPTER V.

COMPARATIVE PHYSIOLOGY OF BINOCULAR VISION.

The cause of the remarkable law of corresponding points, on which all the phenomena of binocular vision depend, has not been traced with certainty to anatomical structure. It is probably in some way connected with the existence of an optic chiasm and the crossing of the fibers of the two optic nerves there, but in what way is not understood. We have already (page 102) alluded to a hypothesis, "the nativistic theory," which supposes that fibers from corresponding points unite into one fiber or end in one brain-cell; but even if this be true, it is undiscoverable. The optic chiasm doubtless is a sign of some kind of sympathetic relation between the two eyes; but whether this necessarily reaches the degree which produces corresponding points is uncertain.

The chiasm exists in nearly all vertebrates, but not in invertebrates. In vertebrates sometimes the fibers of the two nerve-roots (optic tracts) simply cross each other without uniting; this is the case in fishes. In others the fibers of the roots partly cross and partly do not, so that each nerve is made up of fibers from both roots; this is the case in mammals and birds, and probably to some extent in reptiles. It seems certain then that invertebrates do not enjoy binocular vision. It is probable also, from anatomical structure alone, that osseous fishes do not enjoy this faculty. Whether in some still higher animals the sympathetic relation which certainly exists between the two eyes reaches the point necessary for their successful use of the two eyes as one instrument is also, I believe, very doubtful. I proceed to give some reasons for this belief, derived from the position of the two eyes.

In man the axes of the conical eye-sockets diverge about 25°, or each makes with the median line an angle of a little more than 12°. In these slightly diverging conical sockets the eyeballs are so placed, and the muscles so adjusted, that in the waking passive state their axes are parallel; and from this passive parallel condition they may be easily converged even upon very near objects. In man, then, though the eye-sockets still diverge considerably, the eyes are set in front with axes naturally parallel. This is evidently the position most suitable for binocular vision; for the eye-sockets could not be brought any nearer to parallelism without diminishing too much the interocular space, and thus the accuracy of binocular judgment of distance.

In monkeys the position of the eyes is much the same as in man. They are placed well in front, with their axes apparently parallel in the passive state, and therefore well adapted for binocular convergence on near objects. But as we go down the vertebrate scale, the eyes are placed wider and wider apart, then moved more and more to the side of the head; the axes of the eye-sockets are therefore more and more divergent, and the difficulty of convergence on a near point becomes greater and greater, until in some mammals, as cetacea, in many birds, and in all fishes, the eyes are placed no longer in front, but on the sides of the head, with their optic axes inclined nearly or quite 180° with each other. It is evident that animals with eyes so placed can not converge the optic axes on a single point, especially a near point. In fact, it is well known that those birds which have their eyes placed well on the side of the head, when they wish to look attentively, turn the head and *look with one eye.* It seems impossible that animals like the whale and fishes, in which the eyes are fairly on the side of the head, can enjoy a true binocular vision with its consensual movements of the two eyes, with its double and combined images, its stereoscopic effects, and its complex but accurate visual judgments based on these effects. It seems impossible that, for such animals, the law of corresponding points could have been developed, or can now exist; for if it did, it could only, as we have seen (page 260), lead to false judgments as to the direction of objects. They see with two eyes, but these do not act together as one instrument, as a single binocular eye; they are independent, and see each for itself. I have watched the motions of the eyes of fishes swimming in an aquarium, and they seem to me to move *independently* of each other. The same is true of all other senses, even in man: however much their organs may be multiplied, each organ perceives for itself. The property of corresponding points, from which all the phenomena of binocular vision are derived, is something peculiar to the eye of the higher animals. Nothing analogous exists in the other senses. Binocular vision in its perfection, as it exists in man and the higher animals, is the last result of the gradual improvement of that most refined of all the sense-organs, the eye, specially adapting it to meet the wants of the higher faculties of the mind.

There are, it is true, consensual movements and sympathetic relations in the double organs of other senses—e. g., the consensual movements of the hands. There is even a kind of *binaural audition*,* by means of which we judge imperfectly of direction of sound. But these are not only infinitely inferior in degree of perfection to, but they are essentially different in kind from, that consensual movement and that sympathetic relation which we find in the eyes, and which slowly in the process of evolution gave rise to the wonderful property of corresponding points and the phenomena of binocular vision.

Binocular vision, then, is certainly wanting in invertebrates, for the eyes in these are either immovably fixed, as in insects and many crustaceans, or, if movable, as in snails, etc., their movements are not consensual. N.B. The most perfect eyes among invertebrates are found in cephalopods. These have true recti muscles for turning them about, but from their position they can not move consensually. There is also no optic chiasm in any invertebrate.

Teleost fishes do not enjoy binocular vision, for there is in them no optic chiasm, and the position of their eyes makes it impossible for them to converge their axes on objects, especially near objects. The movements of their eyes also seem to be independent. Sharks and selachians generally have an optic chiasm, and therefore probably more sympathetic connection between the eyes than osseous fishes. It is possible that binocular effects begin first to be developed in these. Yet not only in these, but even in reptiles and some birds, binocular seems to be at least subordinate

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* Thompson, "Philosophical Magazine," vol. iv, p. 274 (1877); vol. vi, p. 383 (1878); "American Journal of Science and Arts," vol. xix, p. 145 (1880); Steinhauser, "Philosophical Magazine," vol. vii, p. 261 (1879).

to *monocular two-eyed* vision (if I may be allowed the expression). The carnivorous birds and all mammals except cetacea seem to enjoy binocular vision very much as man does, though I believe in a less perfect degree.

There is another peculiarity of the human eye, probably closely connected with the highest effects of binocular vision, which still more quickly disappears as we go down the vertebrate scale. I refer to the existence of the central spot of the retina. We have already seen that this spot, situated exactly in the center of the retinal concave, and therefore just where the visual line pierces the retina, is the most highly organized and sensitive portion of the retina. It is not more than a millimetre in diameter. Now every spot of the retina has its representative in the field of view. The representative of this is the point of sight and a very small area about that point, viz., the area of very clear vision. At the ordinary reading distance of 12 inches, this area is not more than three quarters of an inch in diameter. If, while gazing steadily and attentively at one point, we observe the relative distinctness of points in other portions of the field of view, we shall find that these become rapidly less and less distinct as the point is more distant from the line of sight. In other words, there is a regular gradation of distinctness, from the point of sight, where it is greatest, to the extreme margins of the field of view, where it is least. Now, as the retina corresponds to the field of view point for point, it follows that there is a regular gradation in keenness and definiteness of perception, and therefore in fineness of organization, from the central spot, where it is greatest, to the anterior margin of the retina, where it is least. This superior fineness of organization has not been demonstrated except for the central spot; but the gradation of distinctness of vision is its representative, and therefore its sign, in the field of view.

Now, as we go down the vertebrate scale, the central spot is found only in the higher monkeys. After a total absence in all other mammals and all birds, it is said to reappear in some lizards, especially the chameleon. But whether in these the organization of this spot is similar to that in man—whether it is really a central spot in the same sense, and has the same significance in vision or not—may be still a question. It seems fair to conclude, therefore, that the graduation of distinctness toward the point of sight, and the limitation of the greatest distinctness to that point, which we find in man, do not exist, at least to the same degree, in most of the lower animals.

The importance of a central spot in the highest animals, and especially in man, is very evident. The limitation of the greatest distinctness to the point of sight is absolutely necessary to the *concentration and limitation of the most thoughtful attention to that point.* If all portions of the retina were similarly organized, and therefore all points in the field of view equally distinct, it would be impossible to fix the attention steadily and thoughtfully on any one point to the exclusion of others. We might *see* equally well, and over a wider area; but we could not *look* attentively at anything; we could not *observe* thoughtfully. But in the lower animals, especially those, as the ruminants, which are preyed upon by others, it is far more important to see well in every direction, than to fix attention exclusively on one point; therefore the advantages of exquisite microscopic distinctness of the center of the field is sacrificed for the much greater advantages of moderate distinctness over a very wide field. The most important thing for them is a very wide field and the equal distribution of attention over every part. Hence their eyes are prominent, set wide apart on the margins of a broad front, and destitute of central spot; so that they sweep the whole horizon, and see all parts with nearly equal distinctness.

It may be said that the sight of these animals is equal or even superior to that of man, and therefore the organization of their retina is probably as fine as that of our central spot. I answer that there are two things to be considered in this connection. The one is *sensitiveness to light*, and therefore perception of the *presence of objects;* the other is *distinctness of the perception of form.* The one gives us notice of the existence of objects, the other gives us distinct knowledge concerning these objects. It is this latter which depends on the fineness of organization of the bacillary layer. Other portions of the human retina are even more sensitive to light than the central spot, as is shown by the well-known fact that we see a faint star by looking a little way from it, when we can not see it by looking directly at it. But distinctness of form is perceived only by the central spot. It seems probable, therefore, that animals destitute of a central spot, although they may have a more delicate perception of the existence of objects in the field of view than we, yet do not see the form of objects regarded as distinctly as we do. For this reason they are more apt to mistake the nature of objects, and therefore more easily frightened by trifling causes.

Again, it is well to observe that the chameleon, in which the central spot seems to reappear, is an animal whose habits and mode of taking its food require the most fixed and undivided attention.

The close connection of the central spot with binocular vision is also quite evident. The central spot, more than all other portions of the retina, is endowed with the properties of corresponding points; and the somewhat complex binocular judgments expressed by the term "stereoscopic perspective" are accurate and reliable only at and in the vicinity of the point of sight. This fact constitutes the great difficulty in the way of the experimental determination of the horopter, as already explained (page 197). It is therefore, to say the least, doubtful if animals whose eyes want the central spots are able to judge as accurately of the relative distance and the solid forms of near objects as we do.

The following, then, are the general changes in the vertebrate eye as we go up the scale: 1. A gradual change of the position of the eyes from the sides to the front of the head, and a consequent change of the angle of inclination of the optic axes from 180° to parallelism; 2. A regularly increasing graduation in the fineness of the bacillary layer of the retina, and therefore in the accuracy of the perception of form, from the anterior margins toward the central parts, so as finally to form in monkeys and in man a specially organized *central spot;* 3. A gradually increasing power of converging the optic axes on a single near point, so that the images of that point may fall on the central spots of both eyes; 4. The gradual evolution of the properties of corresponding points, and therefore of all the distinctive phenomena of binocular vision.

These changes seem all intimately connected with each other and with the development of the higher faculties of the mind.

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