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ART. XI.—*On some phenomena of Binocular Vision;* by JOSEPH LECONTE, Prof. Chem. and Geol. in University of South Carolina.

[Continued from page 77.]

II. *Rotation of the eye on the optic axis.*

NEARLY all the experiments described in this paper had already been made and the results obtained, when my attention was called to Helmholtz's Croonian lecture "On the normal motions of the eye in relation to binocular vision."* From this lecture I received some useful hints, as to the best method of experimenting on this subject, which have been of great service to me, and have made my results much more satisfactory, without, however, materially modifying them. As these results differ very greatly and fundamentally from those of Helmholtz, I repeated the experiments daily for many weeks, modifying them in every conceivable way, to avoid the possibility of error. I am perfectly sure, therefore, that the results are true for my own eyes, and as far as I have been able to have them verified, they are true also for most other normal eyes. Unfortunately, however, the difficulty of verification for other eyes is very great. Many of these experiments which I find perfectly easy are almost impossible for most persons.

Helmholtz's lecture, I suppose, is the most authoritative statement which we have of the present condition of science on

* Proc. Roy. Soc., April, 1864, vol. xiii, p. 186.

the subjects of the motions of the eye and of the Horopter. It seems to be an abstract of more extended researches which I have not seen. On this account it is obscure in some parts; yet I think I cannot be mistaken in his general results. In order to make myself clear, whether in discussing Helmholtz's results or in describing my own experiments, I find it necessary to define the terms I shall most frequently use. The position of the eye when the optic axes are parallel and at right angles to the vertical line of the face, as when with head erect we look at a point on a distant horizon, is called by Helmholtz the *primary direction of the eye*, and the visual line in this case is the *primary direction of the visual line.* All other directions are called *secondary directions.* A plane which passes through the visual line is called a *meridian plane of the eye*, and the intersection of such a plane with the retina we will call a *meridian of the eye.* The *vertical line of demarkation* is that meridian of the eye upon which the image of an apparently vertical line falls when we look directly at the line, and which therefore divides the retina into two equal halves containing corresponding points in the two eyes. The *horizontal line of demarkation* is that meridian of the eye upon which under similar circumstances the image of an apparently horizontal line falls. The plane which passes through the two visual lines we will call the *visual plane*, and that visual plane which is at right angles to the line of the face the *primary visual plane.* The line joining the root of the nose and the point of sight, and which therefore bisects the angle of optic convergence, we will call the *median line of sight.*

Now Helmholtz gives as the law controlling all the movements of the eye the following, viz: that when the eye turns from its primary to any secondary position, *it turns "on a fixed axis which is normal both to the primary and to the secondary visual line."* In other words, the eye may turn on any axis at right angles to the optic axis, but *does not rotate about the optic axis.* Again he states that "vertical and horizontal lines keep their vertical or horizontal position in the field of vision when the eye is moved from its primary direction vertically or horizontally." This law had been previously stated by Listing but without proof; Helmholtz claims to have established it by experiment. His method is very ingenious. It is well known that if we look for some time at a bright object, and then turn the eye upon a comparatively obscure field, a spectrum having the form of the object will be seen. As such spectra are the result of a temporary modification of the retina itself, they must follow the motions of the eye with the greatest exactness. If therefore the bright object be a *line*, then if there be any rotation of the eye on the optic axis, in turning the eye in various directions the linear spectrum ought to incline to one side or the other. Suppose, then, the object be a bright red vertical line on a gray wall at the exact height of the eye: Helmholtz finds that on gazing at the bright line with one eye, taking care that the eye shall have its primary direction, and then turning the eye in a horizontal plane to the right or left, *the spectrum retains perfectly its verticality.* "I found," he says, "the results of these experiments in complete agreement with the law of Listing." For the ingenious device of Helmholtz for getting the primary position of the eye we must refer the reader to his lecture. I have tried Helmholtz's experiments with similar results. Nevertheless, I believe it may be demonstrated that though rotation of the eye does not take place under the circumstances of these experiments, yet it does so under other circumstances not touched by them; and that in a manner which deeply affects the question of the Horopter. The law of Listing is doubtless true or nearly true when the eyes move together parallel to each other, but is far from being true in strong convergence. The experiments which follow prove beyond a doubt that in my own case and in most other cases tried, *the eyes in convergence rotate on the optic axes outward, and that the amount of rotation increases with the degree of convergence.* Meissner* has attempted to determine experimentally the position of the Horopter, and from the position thus determined he *infers* the rotation of the eyes; my experiments prove *directly* the rotation of the eyes, and from this as well as from direct experiment I hope to establish the position of the Horopter.

Helmholtz, it is true, admits some degree of rotation of the eye on the optic axis, particularly when the eye makes wide excursions in the field of view; but that he does not regard this as sufficient to interfere seriously with the law of Listing is evident from the form of the Horopter which he deduces. Moreover, according to Helmholtz, these slight rotations are controlled by the law of Donders, viz: "*that the eye returns always into the same position when the visual line is brought into the same direction.*" He regards this law as rigorously exact. "Every position of the visual line," he says, "is connected with a determined and constant degree of rotation." But the experiments about to be described prove that under certain circumstances the law of Donders, too, is far from being true.

We have already stated (p. 73) that when the squares of the ruled diagram (fig. 5) are combined by converging the

* Bib. Un. Archiv. des Scien., II, vol. iii, p. 160.

optic axes, if the amount of convergence be great, the horizontal lines of the two images are distinctly observed to cross each

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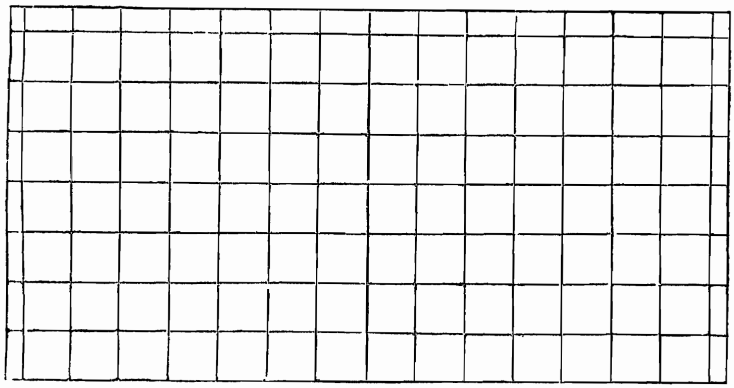

other at small angle. After my attention was once directed to this fact, I could see slight crossing of the horizontals for every degree of convergence, but the verticals seemed to coalesce perfectly. By placing, however, both the diagram and the head perfectly perpendicular, looking straight forward at a point exactly at the same height as the eyes, the visual plane therefore in the primary position, and then slowly increasing or decreasing the convergence of the optic axes, so that the vertical lines of the two images *passed slowly over one another*, it was plainly seen that the verticals of the two images were not parallel, but crossed each other at small angle.

This my original diagram, however, is not well adapted to experiments on this subject for two reasons: 1. It is difficult to distinguish the image of one eye from that of the other. 2. It is difficult to control perfectly the convergence of the eyes. When the vertical lines approach each other, they, as it were, leap and cling together as a single line, even though they really cross at considerable angle; the really crossing lines, by a well known law of stereoscopic combination, being seen as a single line inclined to the visual plane. I therefore constructed a similar diagram, one-half of which consisted of black lines on a white ground and the other half of white lines on a black ground. It is convenient also to have two small circles, one on each half and similarly situated (fig. 6). If I place such a diagram perfectly perpendicularly before me, with the head perfectly erect and the eyes at precisely the same height as the small circles, and then stereoscopically combine the circles by crossing the eyes, I distinctly see the white and black lines, both vertical and horizontal, crossing one another at small angle, as if the images of both eyes had rotated on

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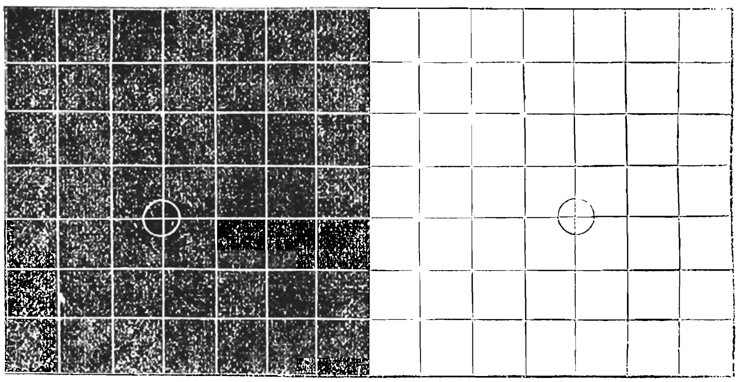

the visual line in opposite directions. This angle of crossing increases as the plane of the diagram is brought nearer and decreases as the diagram is carried farther from the eyes. Or these different angles of crossing may be obtained without moving the diagram or the head, by converging the eyes more and more and causing the white and black vertical lines to pass successively over each other. This is more easily done if there are several small circles on each half, similarly situated but at different distances from each other. In this diagram, the lines being of different colors do not stereoscopically combine easily—they do not cling together as in the other case. Their approach toward or recession from one another and the angle which they make with one another may be marked with the utmost exactness. Nor is there any danger of confounding the two images. For since the eyes are crossed we know that the *white lines* belong to the *right eye* and the *black lines* to the *left eye*, we can therefore determine the direction in which each image rotates. I find always that the black lines or the *image of the left* eye rotates to the right and the white lines or the *image of the right* eye rotates to the left . Now as the image always moves in a direction contrary to the motion of the eye (differing in this respect from spectra), this indicates *a rotation of both eyes on the optic axes outward* .

To test this question still farther I constructed another diagram with the horizontal lines continuous across but the verticals not perfectly vertical, the upper ends of those of the right half inclining to the left and those of the left half to the right by about 1° 20′ (fig. 7). On bringing the circles together I found that at a certain distance of the diagram—but only at a

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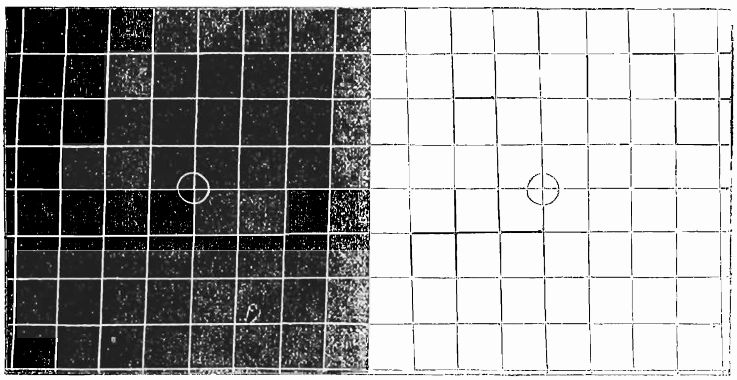

certain distance depending upon the interval between the circles—the *verticals coalesced perfectly;* the horizontals, however, as might be expected, still crossed at a small angle, and in the same direction as before, viz: the whites or right eye image thus ⟋ and the blacks or left eye image thus ⟍, indicating in this case also rotation of each eye outward. *Beyond* the proper distance the verticals approach but do not attain parallelism; *within* the proper distance they cross in a direction contrary to that in the diagram. When the circles are ten inches apart, the proper distance is nearly three feet and the image therefore about seven inches from the eyes.

Helmholtz has a diagram similar in all respects to my own except turned upside down, in which, he states, both verticals and horizontals coincide perfectly when the circles are combined. Our own figure (fig. 7) turned upside down will answer for Prof. Helmholtz's. We quote his own words: "The horizontal lines are parts of the same straight line; the vertical lines are not perfectly vertical. The upper end of those of the right figure are inclined to the *right* and those of the left figure to the left by about $1\frac{1}{4}$ degrees." But his experience differs from our own in a most unaccountable manner. He says: "Now combine the two sides stereoscopically, *either by squinting or by a stereoscope*, and you will see that the white lines of the one coincide with the black lines of the other, as soon as the centers of both figures coincide, although the vertical lines of the two figures are not parallel to each other." He accounts for this, not by rotation of the eyes but by *the* *principle of the difference between real and apparent verticality.* The ignorance of this principle he believes has vitiated the results of all previous observers. He illustrates this principle thus: "When you draw on paper a horizontal line, and another line crossing it exactly at right angles, the right superior angle will appear to your right eye too great and to your left eye too small; the other angles show corresponding deviations. To have an apparently right angle, you must make the vertical line incline by an angle of about $1\frac{1}{4}$ degrees for it to appear really vertical. We must distinguish therefore between the *really* vertical lines and the *apparently* vertical lines in the field of view." "Now look alternately with the right and the left eye at these figures (fig. 7 turned upside down). You will find that the angles of the right figure appear to the right eye equal to right angles, and those of the left figure so appear to the left eye; but the angles of the left figure appear to the right eye to deviate much from a right angle, as also do those of the right figure to the left eye." Prof. Helmholtz therefore believes that the perfect stereoscopic coincidence of the vertical lines of his diagram is the result of this principle. "Therefore," he says, "not the really vertical meridians of the two fields correspond as has been hitherto supposed, but the apparently vertical meridians. On the contrary, the horizontal meridians really correspond at least for normal eyes which are not fatigued."

On this principle Prof. Helmholtz builds his whole theory of the Horopter. But that this principle cannot account for the phenomena he observes I think can be proved. In the first place, I find that if there be any distinction between real and apparent verticality for my eyes, the difference is too small to be detected by the simple observation of lines drawn at right angles with each other. For my own eyes really vertical lines are also apparently vertical, and lines inclined $1\frac{1}{4}$ from verticality are not at all apparently vertical. I have tried several other normal eyes with the same result. But leaving this aside: in the second place, it is by no means indifferent whether the two halves be combined by a "*stereoscope or by squinting.*" If they are combined by a stereoscope as stereoscopes are usually constructed, the right half is looked at by the right eye and the left half by the left eye, so that the point of sight and the plane of combination is *beyond the diagram;* coincidence in this case, therefore, would be a true illustration of Prof. Helmholtz's principle. But if they are combined by squinting, the eyes are crossed, and therefore *the right eye is looking at the left half and the left eye at the right half* of the diagram, and therefore in Prof. Helmholtz's own words, the verticals should "deviate much from a right angle," viz: $2\frac{1}{2}$ degrees. I have tried many eyes and I have yet found *none* in which the coincidence of the verticals of Prof. Helmholtz's diagram was perfect when combined by means of a stereoscope, i. e., beyond the diagram; but I have found *one* person to whom the coincidence seemed to be perfect when the combination was made by squinting.

It is evident, then, that Prof. Helmholtz's principle cannot explain the stereoscopic coincidence by squinting in his own experiment. I myself believe that if the coincidence takes place only by squinting (as in the case mentioned above), it can only be explained by rotation of the eyes *inward.* It is true that in this case the horizontals ought to cross also; but Prof. Helmholtz himself admits that such is sometimes the fact, but attributes it to fatigue. "After keeping the eyes," he says, "a long time looking at a near object, as in reading or writing, I have found that the horizontal lines crossed each other; but they became parallel again when I had looked for some time at a distant object."

On reading Prof. Helmholtz's lecture and finding his results so different from my own, I immediately tried his figure by squinting, but found the verticals cross one another at an inclination much greater than in the diagram itself, while the horizontals also crossed but at a less angle. On turning the figure upside down, however, the verticals coincided perfectly when the proper distance was obtained, though the horizontals crossed as before. All these phenomena are easily explained by rotation of the eyes *outward.* To test the question still more thoroughly, I then constructed other diagrams in which both verticals and horizontals were inclined so as to make an angle of $1\frac{1}{4}$ degrees with the true vertical and the true horizontal (fig. 8) and therefore perfect squares with one another. At the proper distance, when the small circles were brought together, *the coincidence of both verticals and horizontals seemed to be perfect.* When the plane of the diagram was too near or too far, all the lines crossed, in the one case in one direction and in the other case in the other direction. I then constructed still other diagrams, in which the inclination of the lines with the true vertical and the true horizontal were 40 minutes, $2\frac{1}{2}$ degrees and 5 degrees. In all cases I brought the lines in coincidence, but of course by different degrees of convergence. In the last the optic convergence necessary was extreme, and the strain on the eyes considerable; but in the other cases there was not the slightest difficulty or strain. Recollecting, however, that Prof. Helmholtz supposed that the change of position of the horizontals might be the result of fatigue, I tried repeatedly after long rest but always the phenomena were precisely the same. In the diagram in which the

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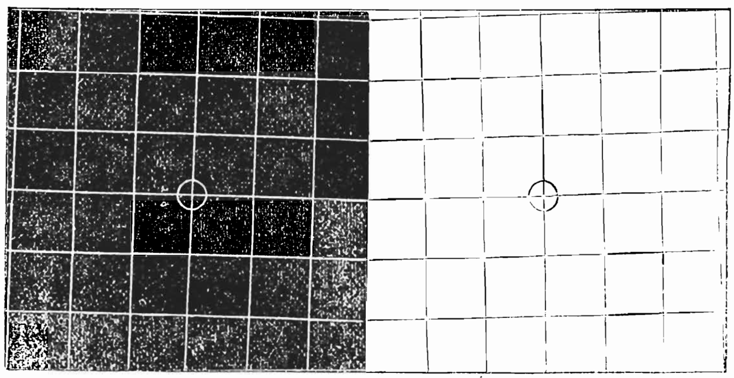

inclination of the lines was five degrees I observed, however, that a *greater degree of convergence was necessary to bring the horizontals in coincidence than to bring the verticals into coincidence.* The difference in the distance of the diagram in the two cases was about two inches and the difference in the distance of the point of sight was about one-half inch. I cannot explain this except by supposing that the form of the optic globe was changed by the excessive action of the muscles.

I can conceive of no possible source of fallacy in these experiments. From long practice they have become almost as easy to me as any ordinary act of vision. They do not now fatigue my eyes in the slightest degree. I see the lines of the two images, which I bring together just as plainly as if they were black and white threads. While watching them I control their motions almost as perfectly as if I was sliding with my hands two frames with white and black threads stretched across them. There is not the shadow of a doubt, therefore, that in my own case the eyes in convergence rotate slightly outward, and that the amount of rotation increases with the degree of convergence.

I next proceeded to determine the amount of rotation for different distances of the point of sight. In the diagram in which the inclination of the lines was 5 degrees, the distance of the image was only 2 to $2\frac{1}{2}$ inches; for the lines inclined $2\frac{1}{2}$ degrees, the distance of the image was 4 inches; for lines inclined $1\frac{1}{4}$ degrees, the distance was 7 inches; and for 40 minutes, the distance was about 12 to 14 inches. I am able, by great strain, to obliterate or nearly obliterate the common field of view of the two eyes. In this case of course the eyes both look at the root of the nose. In this extreme convergence I find that lines coincide which make with each other an angle of 22 degrees or 11 degrees with the vertical. This would seem, therefore, the extreme rotation for my eyes. The distance of the image in this case is nearly at the root of the nose.

If, however, in extreme convergence, rotation on the optic axes takes place to the extent of 11°, this rotation ought to be detectable by means of ocular spectra or even by direct observation of the eye itself. I determined to try these also. My method of experimenting with ocular spectra is as follows: Standing in a somewhat obscure room, I gaze with the left eye (the other being shut) at a vertical crevice in a closed window until a distinct spectrum is obtained. Placing myself now opposite a vertical line on the wall of the room, with my right side toward the wall, I turn my head until my left eye II (fig. 9), looking across the root of my nose *n*, can see the vertical

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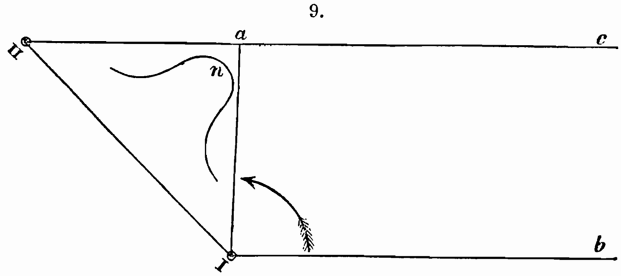

line. I now gaze at a point very near the vertical line, and by inclining my head to one side or the other, bring the spectrum exactly parallel to the vertical line. In this position, if the wall be at some distance from the observer, the axes of the eyes may be regarded as nearly parallel as II*c* I*b*. I now, by a voluntary effort, bring the point of sight along the line II*c* nearer and nearer, until it reaches *a* near the root of the nose. In doing so the spectrum is always seen to incline to the left thus . On relaxing the convergence and looking again at the wall, the spectrum retains its inclined position for an appreciable time and then gradually recovers its original verticality. In similar experiments with the right eye the spectrum is always seen to incline to the right thus .

I next tried direct observation of the eye itself. As I could not find any one with the necessary control over the eyes, I was compelled to make myself the subject of this observation. While therefore, with the right eye shut, I gaze with the left eye across the root of the nose on vacancy, or on a distant object as in the figure (fig. 9), an observer conveniently placed near the visual line carefully examines the iris of my eye so as to recognize the position of the radiating lines. When now, without changing the position of the visual line of the left eye, I turn the right eye inward, as in the previous experiment, until the point of sight is at *a*, the globe of the left eye is distinctly seen to rotate outward. I got four different persons to make this observation upon my eye, and the testimony of all was the same.

I had proceeded thus far in my experiments when I was led to reflect farther upon the phenomena presented by the diagram in which the lines were highly inclined. In this diagram, it will be remembered, the verticals were combined with more facility than the horizontals. I now repeated all my experiments with more care and with especial reference to this point. As I expected I found the same true for all the diagrams, but the difference was so small that it had escaped detection. This led me to suspect that there might be some truth in Prof. Helmholtz's principle of real and apparent vertical. I therefore constructed many other diagrams to test this point. I constructed first a diagram exactly like figure 6, except that the circles were the same distance apart as my eyes, viz : $2\frac{1}{2}$ inches. On placing this diagram before me and gazing on vacancy, the eyes therefore in their primary position, the circles were brought together. In this experiment the *verticals came together parallel.* I sometimes thought there was a scarcely perceptible inclination in the direction required by Helmholtz's principle, viz : thus /\. If any such inclination really existed, it could not have been more than 10′ for each line with the vertical, or 20′ with one another ; for this angle I can distinctly detect under these circumstances. I next constructed a diagram like Prof. Helmholtz's, except that the outward inclination of the verticals was only 40′ instead of $1\frac{1}{4}°$. On combining the two halves of this diagram by means of a stereoscope, there really seemed to be perfect coincidence of both verticals and horizontals ; but I soon found by trying several, that stereoscopes differ much in this respect. I therefore discarded them as unreliable. On combining the same diagram with the naked eye in the manner of a stereoscope, i. e., beyond the plane of the diagram, the verticals coincided perfectly when the point of sight was about twelve inches distant, but the horizontals very perceptibly crossed, though certainly, I think, at an angle less than 40′—it seemed about 20′. On combining the two halves by squinting (of course turning the diagram upside down), I found the result precisely the same when the point of sight was at the same distance, viz: twelve inches. In the next diagram which I constructed the verticals inclined $1\frac{1}{4}$ degrees and the horizontals 50 minutes, the difference being therefore 25 minutes. In this case both seemed to combine perfectly when the point of sight was distant $7\frac{1}{2}$ inches. The next diagram tried had the verticals inclined 5° and the horizontals 3° 45′, the difference being $1\frac{1}{4}$ degrees. In this case both verticals and horizontals combined perfectly at the distance of 2·2 inches. I then tried one in which the verticals inclined 10°. In this case I could not make perfect coincidence of both verticals and horizontals until the difference of inclination was made as great as 5°. The diagram used is shown reduced in the figure (fig. 10). The point of sight in this

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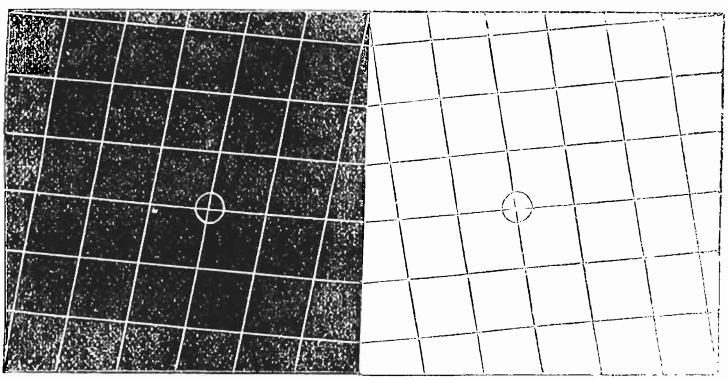


experiment was only $1\frac{1}{4}$ inch from the line joining the optic centers, or about one-quarter inch from the root of the nose.

I attribute these phenomena to a slight distortion of the ocular globe under the action of the oblique muscles—a distortion which increases with the degree of optic convergence. We will refer to this again.

In all the experiments described above the greatest care was taken that the visual plane should be in the primary direction, i. e., at right angles to the line of the face, and especially that the median line of sight should be at right angles to the plane of the diagram. I now wished to try the effect of turning the visual plane upward and downward. Meissner, from his experiments on the position of the Horopter, had arrived at the conclusion that the rotation of the eye was zero, whatever be the degree of convergence, when the visual plane was inclined downward 45° from its primary position, and that the rotation increased as the plane was elevated toward the eyebrows. I was anxious to test this result. The plane of the diagram still remaining vertical I now turned the face upward (taking care, however, that the eyes should still be on an exact level with the circles of the diagram), until the eyes looked in the direction of the point of the nose. In this position, on stereoscopically combining the small circles, the lines, both vertical and horizontal, in all cases *maintained their true position :* i. e., in the diagram with parallel lines (fig. 6), the coincidence of all the lines was perfect, in the diagram with inclined verticals (fig. 7), the horizontals coalesced perfectly and the verticals crossed at their true angle of inclination, while in the diagram with the verticals and horizontals both inclined (fig. 8), both the verticals and horizontals crossed at their true angle of inclination. I tried the same experiment for various distances and therefore various degrees of optic convergence, but always with the same result. *There is*, therefore, *no rotation* of my eyes *when the plane of vision is inclined* 45° *downward.* In continuing the inclination still farther downward I observed a decided rotation of the eyes in the contrary direction, i. e., *inward.* As the eyes are raised from the position, 45° downward, the rotation increases until the visual plane is again in its primary direction. When the visual plane is raised above this, however, I do not find the rotation to increase as stated by Meissner, except in cases of extreme convergence, but rather to decrease again, although it does not again become zero.* In strong convergence, however, as for instance, when the point of sight is less than seven inches distant, the rotation continues to increase as stated by Meissner.

In all these experiments, in order to detect the true rotation, it is absolutely necessary that the median line of sight should be exactly at right angles with the plane of the diagram. The least error in this respect will cause *perspective convergence* of the parallel verticals, or increase or decrease of the angle of inclination of the inclined verticals. With the diagram three feet distant, if my eyes look one inch above or below their true level, on combining the two halves of the diagram I can detect the perspective convergence, upward or downward, with the greatest ease. In all cases, also, but particularly when the convergence is very strong, it is necessary to fix the attention on that horizontal which passes through the small circle, for those above and below converge by perspective.

* More recent experiments, just concluded. have convinced me that in my own eyes, if the convergence is very slight, the outward rotation *does* reach zero and may even be converted into an *inward* rotation. The reason is, that when my eyes are parallel or nearly so, elevation of the visual plane causes *inward* rotation. In some other eyes, however, I have found that elevation of the visual plane when the eyes are parallel causes outward rotation as stated by Meissner. In these cases, therefore, Meissner's results on this point are entirely true.

In these experiments the size of the diagrams is of little importance. I have used them of every size from 5 by 10 inches to 15 by 30 inches.

My next desire was to determine how far these results were general for normal eyes. The great difficulty was to find any one who was able to repeat the experiments. Nevertheless, I have found four young persons with normal eyes who, with some practice, have succeeded in all except the most difficult of them. *Their results agreed perfectly with my own.* In a fifth case, however, in which great difficulty was experienced and the results were uncertain, I was led to believe that the eyes in convergence rotated *inward.* It is not improbable, therefore, that normal eyes differ in this respect.

We believe, therefore, that we are justified in the conclusion that when the eye is in its primary position and therefore passive, the vertical line of demarkation coincides with the vertical meridian and the horizontal line of demarkation with the horizontal meridian of the eye, and therefore these two lines of demarkation are at right angles to each other. But as soon as the eyes begin to converge, the oblique muscles (particularly the inferior oblique) begin to act, rotating the eye on the optic axis and slightly distorting its form; so that the vertical line of demarkation is now not only no longer coincident with the vertical meridian but also no longer at right angles to the horizontal line of demarkation. Both the rotation and the change in the relation of the two lines of demarkation increases with the degree of optic convergence. It is possible that the frequent action of the muscles distorting the globe of the eye may leave some permanent impress upon the form of the globe, so that even in a passive state the vertical line of demarkation does not coincide perfectly with the vertical meridian. If so, then to that extent Helmholtz's principle of real and apparent vertical in the primary position of the eye would be true. Or to express it differently: we have seen that the inclination of the vertical upon the horizontal line of demarkation decreases as the point of sight recedes; at $1\frac{1}{4}$ inches it is 5°, at 2·2 inches it is $1\frac{1}{4}$°, at 7·5 inches it is 25′, and at 12 inches 20′. It is possible that even when the point of sight recedes to infinite distance and the horizontal line of demarkation becomes coincident with the horizontal meridian, the vertical line of demarkation may still make a small angle with the vertical meridian. If so, this angle is the difference between the real and apparent vertical spoken of by Prof. Helmholtz. We do not yet admit this as probable, however, for the natural position in which all lines at all distances combine when the visual plane is inclined 45° downward seems inconsistent with this idea.

The decrease of the rotation of the eye when the visual plane is inclined downward and its increase when the visual plane is inclined upward, seems to be the result of the relative power of the two oblique muscles. Ordinarily the inferior oblique is the stronger and the rotation is therefore outward, but as the visual plane is inclined downward, the action of the two become more and more nearly equal, until at 45° they balance each other and there is no rotation. Below 45° the action of the superior oblique predominates and the eye therefore rotates inward. In turning the visual plane upward and converging strongly, the action of the inferior oblique predominates more and more.

It will be observed that the rotation of the eye which we have demonstrated necessitates, in optic convergence, a difference between the real and apparent vertical; but our views differ entirely from those of Prof. Helmholtz's in the following respects: 1. Prof. Helmholtz admits only a difference between real and apparent *vertical*; we have shown a difference between the real and apparent horizontal as well as the real and apparent vertical. 2. Prof. Helmholtz's difference is a constant one, viz, $1\frac{1}{4}°$; ours varies from 11° to 20′ and probably to zero. 3. According to Prof. Helmholtz the relation of the apparent vertical to the apparent horizontal is a constant one, viz: an angle of about $88\frac{3}{4}°$; our experiments prove that this relation varies to the extent of 5°.

It is certain, therefore, that the law of Listing is far from being true in strong convergence. Evidently the reason is that in convergence muscles are used which are not used in simply turning the eyes from side to side, as in the experiments used by Helmholtz to prove this law (p. 155). That different muscles are used in strong convergence is easily shown as follows: It is easy to turn either eye inward until it looks in the direction of the root of the nose, provided the other eye moves parallel with it, i. e., outward; but it is almost impossible to turn both eyes at the same time so as to look at this point. Great strain is experienced in producing convergence even much short of this. The eyes are turned from side to side, parallel to each other, by means of the interior and exterior recti muscles, while in convergence the oblique muscles are also used. For this reason Prof. Helmholtz's experiments on spectra do not apply to convergence.

The law of Donders is equally untrue for strong convergence. This law asserts that the position of the eye is rigorously constant for every position of the visual line. But in the experiment represented by figure 9 the eye II, *although the direction of its visual line is unchanged, rotates on its axis* when the visual line of the other eye is turned from the direction I*b* to the direction I*a*.

The reason is, that as I. turns toward *a* the oblique muscles in both eyes begin to act. It is probable that the action of the oblique muscles and therefore the rotation of the eye, is *consensual with the two adjustments and with the contraction of the pupil;* and it is well known that under the circumstances represented by the figure, the pupil of the eye II would contract also, although the direction of the visual line is unchanged.

III. *The Horopter.*

If we look intently at any point the visual lines converge and meet at that point. Its image is therefore impressed on exactly corresponding points of the two retinæ, viz: on the central spot of each. A small object at this point is therefore seen single. We have called this point the *point of sight.* All objects beyond or on this side of the point of sight are seen double, for their images do not fall on corresponding points of the two retinæ. But objects above or below, or to one side or the other 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 expressed differently thus: Each eye projects its 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 in coincidence at the point of sight. Now the point of sight, together with all other corresponding points of the two fields of view which coalesce at that moment, constitute the Horopter. Of course the image of all points lying in the Horopter fall on *corresponding points* of the retina.

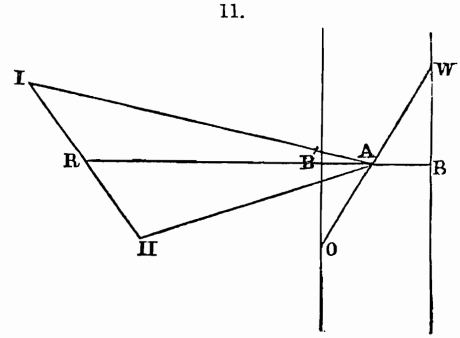
Is the Horopter a surface or is it a line? In either case what is its form and position? These questions have tasked the ingenuity of physicists, mathematicians and physiologists. If the position of identical points of the retinæ under all circumstances was known, then the question of the form of the Horopter would become a purely mathematical one. But the position of identical points evidently depends upon the laws of ocular motion. It is evident, therefore, that it is only on an experimental basis that a true theory of the Horopter can be constructed; and yet the experimental investigation as usually conducted is very unsatisfactory, on account of the indistinctness of vision when the object is at any considerable distance from the point of sight in any direction.

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 point of sight and the optic centers ; others, a torus formed by the revolution of a circle passing through the point of sight and the optic centers, on a line joining the optic centers. The subject has been investigated with great acuteness by P. Prévost, A. Prévost, J. Muller, G. Meissner, E. Claparède,* and lastly by Helmholtz.† A. Prévost determines in it, as he supposes, a circle passing through the optic centers and the point of sight, which he calls the "*horopteric circle*," and a straight line passing through the point of sight at right angles to the visual plane, which he calls the "*horopteric vertical.*"

Until the investigations of Meissner almost all attempts to determine the form of the Horopter have been by mathematical calculations, based upon the doctrine of identical points and assuming the law of Listing. Meissner attempts the same question experimentally. We condense the following account of his admirable investigations from Claparède's memoir of this subject ‡ already referred to :

Let R (fig. 11) be an observer and I II his two eyes, A the point of sight, B an object beyond and B′ an object nearer than the point of sight, but all in the same line, joining the root of the nose and the point of sight. Of course, both B and B′ will be seen double. If, now, while the sight is still fixed upon A, B be elevated, its two images, according to Meissner, will approach, until at some point, W, they coalesce.

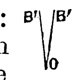
11.



If, on the contrary, B be depressed, its images separate more and more. If, now, B′ be elevated, its images separate, but if it be depressed, its images approach and coalesce at O. The line WAO is, therefore, the Horopter or line of single vision. It is not at right angles but inclined to the plane of vision. Again, according to Meissner, if instead of points we have vertical lines like threads WB and OB′ (fig. 11), then OB′ will

* Bib. Un. Archiv. des Scien., II, vol. iii, p. 138 and 225.

† Proc. Roy. Soc., Apr., 1864. ‡ Bib. Un. Arch. des Scien., vol. iii, p. 138.

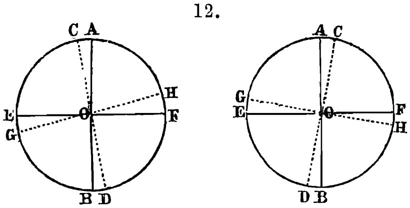
double at B′, the images being crossed, and approach one another and meet at O, in other words, will appear thus : 

while BW will also double at B but not cross (i. e., each image will have the same name as the eye), and will be seen to converge and meet at W thus 

. Lastly, if the vertical line pass through the point of sight A, the images will cross one another like an X.

Meissner accounts for these phenomena by supposing that, in converging the optic axis, the eyes rotate on the optic axis outward so that the vertical lines of demarkation CD no longer coincide perfectly with the vertical meridians AB (fig. 12,) as they do when the eyes are in the primary direction (the axis parallel) but cross them at a small angle. In the primary direction of the eye the image of a vertical line according to Meissner falls on the vertical line of demarkation CD in both eyes (for these lines then coincide with the vertical meridian) and is therefore seen single. But if the eyes rotate on the optic axes outward then the image of a vertical line still falling on the vertical meridian must cross the line of demarkation in opposite directions in the two eyes and therefore cannot be seen single except at the point of sight, the image of which corresponds to the central point O of the retina of each eye. In order that the image of a line shall fall on the line of demarkation in both eyes and thus be seen single, it must be inclined at a certain angle with the vertical, the lower end being nearer and the upper end farther away. It is moreover evident, upon a little reflection, that when the eye rotates the Horopter cannot be a plane nor a surface of any kind, for objects right and left of the horopteric line must all be doubled by displacement of the horizontal line of demarkation GH (fig. 12,) which therefore no longer coincides with the horizontal meridian EF.

12.

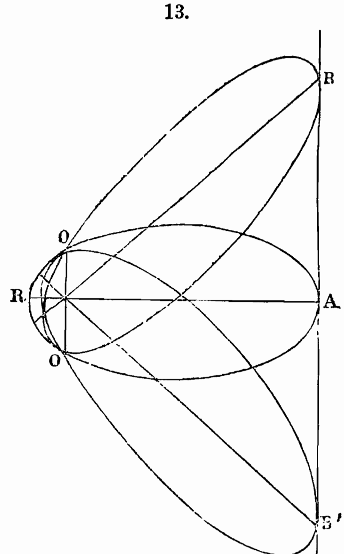


From various experiments made at different distances and with different degrees of inclination of the visual plane upward and downward, Meissner concludes : 1. That looking straight forward at an infinite distance the Horopter is a plane at right angles to the visual lines. 2. That for all other distances, the visual plane remaining the same, the Horopter is a straight line passing through the point of sight and increasing in inclination to the visual plane, as the convergence of the optic axes increases. 3. That in turning the visual plane downward, the inclination of the horopteric line with that plane becomes less and less, until at 45° downward it becomes perpendicular and therefore the Horopter again expands into a plane at right angles to the median line of sight. 4. That in raising the visual plane upward toward the eyebrows, the inclination of the Horopter to the visual plane increases.

We have given Meissner's investigations more in detail, because by entirely different methods we have confirmed almost all of them.

Claparède by similar experiments fails to confirm the conclusions of Meissner and therefore rejects them. He concludes, partly from his own experiments and partly from calculation, that "the Horopter is a surface of such a form that it contains a straight line perpendicular to the plane of vision and passing through the point of sight, and that every plane passing through the optic centers makes by intersection of this surface, the circumference of a circle." In other words, he believes that the horopter is a surface which contains the horopteric vertical BAB′ (fig. 13) and the horopteric circle OAO of Prévost, and that in addition the surface is further characterized by the fact that, while the point of sight remains at A, the intersection with it of every plane passing through the optic centers OO upward or downward as OBO and OB′O is also a circle. It is evident that as these circles would increase in size upward and downward the Horopter according to Claparède, must be a surface of singular and complex form.

13.



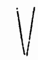
Finally, Helmholtz arrives at results entirely different from all previous observers. He sums up his conclusions as follows:

"When the point of convergence is situated in the middle [vertical] plane of the head, the Horopter is composed of a straight line drawn through the point of convergence [direction not stated but evidently not at right angles to the visual plane, for see below the sentence marked[a]] and a conic section passing through the optic centers and intersecting the straight line."

"When the point of convergence is in the plane which contains the primary visual lines [primary visual plane], the Horopter is a circle going through that point and the optic centers [Prévost's horopteric circle] and a straight line intersecting the circle [where and in what direction not stated]."

"When the point of convergence is situated as well in the middle plane of the head as in the primary visual plane, the Horopter is the circle just described [Prévost's horopteric circle] and a straight line going through that point [direction not stated]."

"There is but one case in which the Horopter is really a plane, viz: when the point of convergence is in the middle plane of the head and at an infinite distance. Then the Horopter is a plane *parallel* to the visual plane and *beneath* it, at a certain distance which depends upon the angle between the *really* and *apparently vertical* meridians, but 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 at a point on the horizon, the *Horopter is the ground on which we stand.* [a] When we look at the ground on which we stand at any point equally distant from both eyes, the Horopter is not a plane, but the straight line which is one of its parts *coincides completely with the horizontal plane on which we stand.*"

These conclusions of Helmholtz are the result of refined mathematical calculations *based entirely upon the supposed constant difference between the real and apparent vertical.* If this principle be true for all normal eyes, then it is probable that Helmholtz's conclusions in regard to the form and position of the Horopter are also true for those cases in which the point of sight is at considerable distance and in which, therefore, the rotation of the eye is very small. I am not able to test all of Prof. Helmholtz's conclusions by calculations based upon this principle, but I easily see that the position of the Horopter lying along the ground is the necessary consequence of a difference of $1\frac{1}{4}$ degrees between the real and apparent vertical when the eyes are in their primary direction. For if a line be drawn from each pupil downward, making an angle of $2\frac{1}{2}°$ with each other or of $1\frac{1}{4}°$ with the vertical, they would intersect each other at the distance of about five feet below the eyes or about the feet of the observer standing erect. Now if these two lines be placed thus  before the observer whose eyes are in the primary direction, it is plain that their stereoscopic combination would be a line lying along the ground to infinite distance. If the difference between the real and apparent vertical be less than $1\frac{1}{4}°$, then the distance below the eyes of the horopteric plane would be greater. We have already shown that if there be any such difference in our own eyes, it cannot be more than 10′; in this case the horopteric plane would be at least 35–40 feet below the eyes. But Prof. Helmholtz takes no account of rotation of the eyes on the optic axes, which greatly affects the form and position of the Horopter when the point of sight is near; and we believe that it is only when the point of sight is near, that the form and position of the Horopter is of any practical importance in vision, for it is only then that the doubling of images lying out of the Horopter is perceptible.

It has been with much hesitation that I have ventured to criticise the conclusions of so distinguished a physicist. My ability to do so, if well founded, I attribute entirely to a facility in the use of the eyes such as I have never seen equalled in the case of any other person.

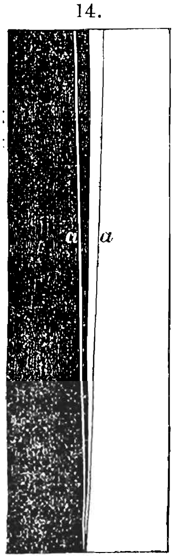
Although, I believe, Meissner has arrived at truer results than any one who has yet written on this subject; yet I think his method very unsatisfactory. I have wondered at the skill and patienee which could attain such true results by such imperfect methods. I have tried Meissner's experiments without any satisfactory results, and I confess I commenced these experiments with the conviction that his theory was untenable; but contrary to my expectation his views have been in a great measure confirmed. The difficulty with Meissner's method and in fact with all previous experimental methods, as already stated, is the indistinctness of objects at any considerable distance from the point of sight in any direction. In Meissner's experiment with the three points, B′, A and B (fig. 11), in lowering B′ or elevating B, the indistinctness was so great that I could not tell with certainty whether the images approached each other or not; and in his second experiment with the thread, the obstinate disposition on the part of the eye to see single by stereoscopic combination even when the images cross, interferes seriously with the certainty of the result. But in my experiments, by virtue of the complete dissociation of the axial and focal adjustments, the lines are seen perfectly clearly; and by making them pass each other slowly, their relation to each other may be observed with great exactness.

I will now state my own results in regard to the Horopter.

It is evident that if, in convergence, the eyes rotate on the optic axes as my experiments prove, then in this state of the eyes the Horopter cannot be a surface, but a line; and this line cannot be vertical but inclined to the visual plane. Perhaps this requires farther explanation. If the eyes in a state of convergence be fixed on a vertical line, then if the eyes rotate the line must be doubled except at the point of sight. This doubling is the result of *horizontal* displacement of the two images in opposite directions, and therefore the two images may be brought together by bringing the doubled portion of the vertical line nearer or carrying it farther away. This is done in inclining the line as in fig. 11. But all points to the right and left of the horopteric line are also doubled by rotation, but this doubling is the result of *vertical displacement* of the images; now vertical displacement cannot be remedied by increasing or decreasing the distance, because *the eyes are separated horizontally*. Therefore no form of surface can satisfy the conditions of single vision right and left of the horopteric line. The restriction of the Horopter to a straight line and the inclination of that line to the visual plane are therefore necessary results of rotation on the optic axes. But I have also proved this by direct experiment.

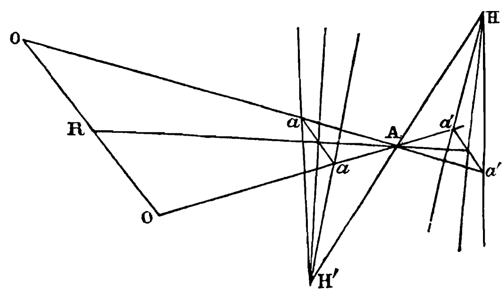
If two lines, one white on black and the other black on white (fig. 14) be drawn at an angle of $1\frac{1}{4}$ degrees with the vertical and therefore $2\frac{1}{2}$ degrees with each other, then by bringing my eyes so near to them at any point *aa* (taking care that the median line of sight shall be perpendicular to the plane of the lines) that the visual lines without crossing shall meet beyond the diagram at the distance of seven inches from the eyes, the two lines are brought in perfect coincidence. If on the contrary the same figure be turned upside down and the eyes be placed a little farther than seven inches, so that the two points *aa* are brought together by crossing the optic axes at the distance of seven inches, then also the lines are brought in perfect coincidence. The accompanying figure (fig. 15) in which OO are the eyes, A the point of sight, *a*H, *a*H and *a*'H', *a*'H' are the lines in the two positions, will explain how the stereoscopic combination takes place in each case. The line HAH is the Horopter. This experiment is difficult to perform satisfactorily. When the lines come together it is difficult to determine whether there is real coincidence or not. I have observed, however, that when the coincidence is not perfect the white and black lines seem to run spirally round each other. The best plan is to observe them at the moment of coming together or of separating. I feel quite confident of the reliability of the conclusions reached.

14.



I made many calculations based upon these experiments and on the previous experiments on rotation of the eye, to determine the inclination of the horopteric line for different degrees of convergence, i. e., for different distances of the point of sight. The results of these calculations were not entirely satisfactory. I had expected from Meissner's results that there would be found a progressive increase as the distance decreased. But I could not be sure from my calculations of any increase or decrease with distance. For all distances the inclination seemed to come out about seven degrees—in some a little less, in some a little more. Beyond three inches there seems to be a slight progressive increase rather than decrease ; within three inches the action of the eyes was irregular.

15.



I then adopted another method. I used the diagram of parallel lines (fig. 6,) and inclined it at an angle of exactly 7° from the perpendicular in the supposed direction of the Horopter, and at the distance of 3 feet. In this position the verticals of course all converge by perspective. I then brought together successively the lines 3 inches apart, then those 6 inches apart, then those 9 inches, 12 inches, 15 inches, 18 inches and so on even to the last, which were 30 inches apart: *in each case the lines seemed to come together parallel* or at least the divergence, if any, was so small that I could not be sure about it. Now in this experiment the point of sight varied from 16½ inches to only 2·8 inches in distance, and yet the inclination of the horopteric line seemed to be nearly the same for all, viz: 7°. If there was any difference at all it seemed to be in favor of *greater inclination at greater distance.* This result which I arrived at, though doubtfully by experiment alone, would be the necessary result of any residual difference between the real and apparent vertical, or in other words, any residual inclination of the vertical upon the horizontal line of demarkation of the eye in its primary position, such as Helmholtz maintains and as I have supposed possible. Still it by no means proves the existence of this residual difference.

It must not be supposed, however, because the lines 3 inches, 6 inches, 9 inches, 12 inches, &c., apart, are all brought into coincidence at the same or nearly the same inclination, that therefore the amount of rotation of the eye is the same for all. The perspective convergence of the lines, of course increases with their distance apart, and therefore the rotation of the eye necessary to bring them successively into coincidence increases also. It is quite possible that the rotation should increase with the optic convergence, and yet the inclination of the horopteric line remain constant or even decrease with the convergence. Whether the inclination of the horopteric line increases or decreases with distance would depend upon the law of increase of rotation with increasing convergence. If it increases with distance then it is possible that when we look at the ground before us the Horopter may be a line lying along the ground, as maintained by Helmholtz.

I next tried the same experiments with the eyes inclined downward 45°. The *lines do not change at all their natural perspective convergence.* In all the experiments made with eyes in this position the inclination of the lines in the image was the same as in the object. I conclude therefore that in this position of the eyes the Horopter is at right-angles to the plane of vision, and since there is no rotation of the eye the Horopter in this position expands *into a surface.* Below this inclination *the Horopter again becomes a line but inclined now the other way, i. e., the upper end toward the observer.* In turning the eyes upward toward the eyebrows, I have found the rotation, except in cases of strong convergence, less than looking straight forward. I conclude therefore that in this position the horopteric line inclines less to the visual plane than it does when the visual plane is in its primary direction.*

The points in which my experiments do not confirm Meissner are—1, the increasing inclination of the horopteric line with increasing convergence. 2, the increasing rotation of the eye as well as inclination of the horopteric line under all circumstances in turning the eye upward. Again, I believe that Meissner is also wrong in supposing that the Horopter is a *plane* when the eyes are depressed 45°. In this position it is a *surface* but not a plane. It is clear that the images of points situated to the right and left of the point of sight and in the same plane with it cannot fall on corresponding points of the two retinæ. As to the form of this surface, I feel myself unequal to the task of its mathematical investigation, and its experimental investigation presents, I believe, insuperable difficulties.

We have seen that the eye in convergence rotates on the optic axis. The question naturally occurs, is this rotation to be regarded in the light of an imperfection of the instrument (of which there are several examples in the structure and mechanism of the eye,) and should the law of Listing be regarded as

* As stated in note on p. 165, eyes certainly differ in this respect. In my own, if convergence be small, the outward rotation decreases with the elevation of the visual plane, becomes zero, and even is converted into an *inward* rotation; the inclination of the Horopter, therefore, decreases, *becomes perpendicular and even inclines the other way.* In some other eyes the outward rotation increases whatever be the convergence; in this case, of course, the inclination of the Horopter increases as stated by Meissner.

the ideal of ocular motion, though an ideal seldom or never realized in nature; or does the rotation of the eye subserve some useful purpose in vision ? I believe there is no doubt that the latter view is the correct one, for there seems to be special muscles which are adapted for this rotation and the action of these muscles is consensual with the adjustments of the eye and the contraction of the pupil. This purpose I explain as follows. A general view of objects in an extended field is absolutely necessary to animal life in its highest phases, but an equal distinctness of all objects in this field would only distract the attention. Therefore the eye is so constructed and moved, as to restrict as much as possible both *distinct* vision and *single* vision. Thus as in *monocular vision* the more elaborate structure of the *central spot* of the retina restricts distinct vision to the visual line, and the *focal adjustment* still farther restricts it to a single point in that line; so also in *binocular* vision, *axial adjustment* restricts single vision to the Horopter, while rotation restricts the Horopter to a single line.

Conclusions.

The most important conclusions arrived at in this paper may be briefly summed up as follows.

1. The axial and focal adjustments of the eye are not so inseparably associated as is generally supposed ; but on the contrary when distinctness of vision requires it they may be completely dissociated.*

2. In this dissociation, the contraction of the pupil associates itself with the focal in preference to the axial adjustment.

3. In optic convergence there is a rotation of both eyes on optic axes *outward* ; and this rotation increases with the degree of convergence.

4. In inclining the visual plane downward the rotation of the eyes for the same degree of convergence decreases, until when the visual plane is inclined 45° downward the rotation becomes zero for all degrees of convergence. Below the inclination of 45° the rotation is *inward.* In turning the eyes upward, except in cases of strong convergence, the rotation also decreases slightly but does not reach zero ;† in strong convergence it increases as stated by Meissner.

5. Besides the rotation produced by optic convergence there is also a decided inclination of the vertical line of demarkation upon the horizontal line of demarkation, which increases with the degree of convergence. This change in the relation of these two lines is probably the result of distortion of the ocular globe.

* While these pages were passing through the press, I discovered that in this conclusion I had been anticipated by Donders and others. All previous experiments, however, were made by means of glasses. Mine were made with the naked eye.

† See this statement modified in note on p. 165.

6. As a necessary consequence of the rotation of the eyes, for all degrees of convergence 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 increases or decreases with distance I have not been able to determine with certainty. It probably increases with distance.

7. In inclining the visual plane below the primary position, the inclination of the horopteric line becomes less and less until when the visual plane is lowered 45° the horopteric line becomes perpendicular to that plane and at the same time expands into a surface. Below 45° the Horopter again becomes a line, but now inclined in the contrary direction, i. e., the *upper* end nearer the observer.

8. In inclining the visual plane upward or toward the brows, if the optic convergence be strong, the inclination of the horopteric line increases, but if the optic convergence be small it decreases but does not reach zero or become perpendicular.*

9. In looking downward 45° for all distances the Horopter is a *surface* passing through the point of sight and perpendicular to the median line of sight, but the form of the surface I have not attempted to determine. In looking straight forward at infinite distance the Horopter is also a *surface* passing through the point of sight, but the inclination of this surface I am unable to determine.

10. It is possible that in some eyes which would be considered normal there is, in convergence, a rotation of the eyes *inward*, probably from greater power in the *superior* oblique. In such cases the position of the Horopter would be different.

Columbia, S. C., Nov. 16, 1868.