THESIS

FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

INVESTIGATIONS ON DEPTH PERCEPTION IN INDIRECT VISION

by

Józef L. Zając

/Doctor of Philosophy, Cracow University/

Edinburgh, May 1951.

CONTENTS.

I

HISTORICAL INTRODUCTION.

The problem of the relations and the differences between the monocular and the binocular space perception has frequently been the subject of experimental as well as of theoretical investigations. In particular, different concepts of depth perception in monocular and binocular visions were formulated on the basis of various factors taken into account, some of which I will mention and discuss here. These were based among others on

a/ various philosophical approaches / nativism, empirism, vitalism, etc. / ,

b/ geometrical constructs,

c/ various hypotheses as to the nature of physiological processes / accommodation, convergence of the eyes, changes in the pupils, various processes occurring on the retina and the central nervous system/,

d/ psychological assumptions / field, energy, etc. /.

Different authors and workers in the field of space perception represented different concepts and points of view just mentioned which were very often mixed together.

In order to discuss various ways in which the phenomena of depth perception were described and

and explained, first of all the main features and problems of our normal vision in the third dimension must be mentioned.

1/ What is our depth perception of an object if we fixate this object i.e. when the eyes are converged on it, that is when both visual axes of the eyes intersect on it; this results in the formation of the images of that object on the foveas. In the case when the object lies within the range of accommodation of both eyes its images formed on the respective retinas are sharp and we see the object very distinctly because both eyes can be properly accommodated on it. But if the object lies outside the range of accommocation of one or both eyes we can still fixate on it, i.e. converge the visual axes, and the images are formed on foveas but one or both eyes are not accommodated on it, the images of one or both eyes are not sharp but diffused and we see the object not so distinctly but blurred.

In the case of monocular fixation accommodation only is involved as far as concerns the space perception phenomena, the convergence may take place or not but it is of no importance.

Yet the changes in the pupil may have some influence on depth perception of fixated objects.

2/ The second group of problems concerns the

the depth perception of objects in indirect vision i.e. when we fixate one object and observe the distance of objects situated laterally, the retinal images of which are formed outside the fovea. This can be done in monocular as well as binocular vision. In the binocular vision different cases might occur :

a/ The laterally situated objects may be seen singly. This occurs when these objects lie in the so called horopter. In this case the objects are seen sharply if placed within the range of accommodation of the eyes, and blurred if outside this range. The objects situated within a short distance from the horopter are seen singly but more blurred because they do not cover one another but only overlap.

b/ When the objects are situated at a greater distance from the horopter they are seen double in the so called double images which are crossed if the object is situated in front of the horopter, and uncrossed when the object is behind the horopter.

c/ The so called stereoscopic vision is a special case of binocular vision; it occurs when two different but similar objects are placed in front of each eye and are seen as a single object. This effect can be obtained in a natural setting when we place a fixation object in front or behind or between the other objects, or by a special arrangement

arrangement in different kinds of stereoscopes.

In this whole group of problems we might look for similarities and differences, for relations between monocular and binocular vision. In this thesis the results of investigations of phenomena falling into the groups b/ and c/ are principally described.

3/ The third group consists of problems, how we see in the third dimension when the eye or eyes are moving about i.e. change the real or imaginary fixation point, or when the objects are moving in the field of vision. This is connected with changes of accommodation and convergence. Some of these investigations were concerned with such problems.

4/ Other group consists of problems concerning the depth perception of distant objects, of objects situated at great lateral angles, depth perception in dark adaptation and other special cases.

5/ The so called illusions, inversions, etc. which are connected with problems ad 1/, 2/, 3/, and 4/.

When we speak of the difference in the depth perception in different cases we may distinquish between a/ the vision of distance and b/ the estimates of distance. If we fixate an object we cannot see it at a distance say of 15 or 100 yards from us. But we can say that we estimate this distance as 15

15 or 100 yards. But we can see, for example, that an object is nearer or further away than, or equidistant with the object which we fixate. The failure to distinquish between these two aspects led several times to confusion and to misinterpretation of results of investigations. All the so called"clues" are connected rather with the estimates of distance than with seeing of depth; nevertheless many authors tried to explain by them the vision of distance and further they tried from the non visual elements like muscular sensations to arrive at seeing in the third dimension.

These investigations are mainly concerned with conditions and phenomena of vision in the third dimension and not of estimates of distance.

In connection with these different problems historical examples of proposed solutions will be discussed with special reference to those which were concerned with the relations between monocular and binocular vision and which at the same time illustrated the part played bby accommodation, convergence and disparity on the retinas.

A. The projectionists' theories.

One of the first promotors of investigations on visual space perception was Aquilonus [1], contemporary

contemporary of Kepler, who originated the theory that the images formed on the retina are projected to the outside. Aquilonus introduced the conception of the horopter as a plane passing through the fixation point and perpendicular to the plane containing the visual axes of the eyes. He considered this plane of the horopter as a locus of projections of all images formed on the retinas. Aquilonus was the first initiator of the simplest projection theory of vision. This theory concerns in the first place binocular vision in single and double images. The fixation object is seen in the place where the visual axes of both eyes intersect. Monocular vision is according to Aquilonus not threedimensional because one might project the images on the retina anywhere along the visual lines. In the XIX century several authors like Schultz,[38/] Nagel[33/34/], Meissner[31/], Donders[11/] and others followed Aquilonus and developed the projectionists' theories in various forms. Their concepts of visual space were discussed in the author's paper : " La localisation en profondeur des images doubles "[52/]. Here a summary only will be given.

" 1/ The localisation of the double images results in this theory from various types of projections of the images formed on the retina. In general these double images are seen in a plane without any depth. As concerns the objects seen in in the double images the projectionists' theories admit that this is not a question of seeing in the third dimension but only of an estimate of distance.

2/ Concerning the relation of the depth perception of double images in binocular vision with monocular vision, the projectionsists' theories give only one reply. If the distance of an object is defined only by the intersection of the visual axes of both eyes, in the case of monocular vision the distance cannot be determined since there is no intersection of the visual axes at all."

The projectionists' theories have been criticised by many authors, and what is more important have been disproved by the facts.

B. Associationists' theories.

Another line of thought was followed by Berkeley.[3/] In opposition to those theories which were based on geometrical constructs Berkeley based his theory on certain sensations of kinaesthetic, muscular nature and others which resulted in space perception. He states that the estimate of distance of objects situated far away is rather a judgment based principally on experience and not on sensations, but the distance of near objects may be perceived by sensations which arise when the eyes looking at a a near object converge and when by a muscular effort of the eyes we prevent the objects from being seen blurred. Then in accordance with Berkeley's views through the convergence and the accommodation of the eyes / as muscular sensation and as geometrical constructs as in the projectionists' theories / we receive the basic sensations. Berkeley said[3/]: " When we look at a near object with both eyes according as it approaches or recedes from us we alter the disposition of our eyes by lessening or widening the distance between the pupils. This disposition or turn of the eyes is attended with a sensation which seems to me to be that which in this case brings the idea of greater or lesser distance into the mind." ....." Not that there is any natural or necessary connection between the sensation we perceive by the turn of the eyes and the greater or lesser distance but because the mind has by constant experience found the different sensation corresponding to the different dispositions of the eyes to be attended each with different degree of distance of the object, there has grown up a habitual or customary connection between those two sorts of ideas." And he went on to stress the role of experience in the association of these two ideas and to discredit Descartes' view that one perceives actually the angle of the eyes in order to apply a natural geometry in the judgment

judgment of distance / Descartes has also based his theory of vision on geometrical constructs like Aquilonus / .

According to Berkeley the meaning of saying that we see some object at a distance of so many yards is that we may reach this object by an appropriate effort of our muscles. One further remark by Berkeley is worth mentioning here because of the connection with the experiments described here i.e. that we see the near objects blurred and confused because according to his views the seeing of near objects is associated with the blurredness and confusion and the seeing of objects situated far away is accompanied by clearness and distinctness. This view of Berkeley however is not confirmed by facts.

The associationists' views concerning depth perception initiated by Berkeley and based on the connection of perceptions or estimates of distance with the muscular sensations accompanying the changes of accommodation and efforts of convergence prevailed for a very long time in the physiology and psychology of depth perception.

One of the representatives of the associationists' theories in the form of the so called unconcious inference is the famous scientist in the field of physiological opticts as in many other fields,

19/20/
fields, H.V.Helmholtz. According to his views monocular vision does not involve any perception of distance. There is only an estimate of difference of distance based on the differences of angles subtended by the objects seen indirectly and those fixated / unconcious inference / .As concerns the estimate of distance by binocular vision it is most accurate for objects situated in the horopter / defined in a different way from Aquilonus / which are seen singly. It is less accurate for points situated further away from the horopter but not so far as to be seen in the double images. The least accurate is that estimation when the objects are seen in distinct double images and the less accurate the greater the lateral distance between them.

According to Helmholtz the double images are not seen as has been thought previously at the same distance as the fixation point / Aquilonus / and are not projected on the imaginary plane of the horopter. The double images are seen at the distance at which the object is situated. Only in the case when two double images are very far apart from each other which occurs when this object is situated very far from the fixation point situated near to the eyes- - the perception of distance of the double images ceases altogether and we can only estimate the distance on the basis of comparison of the visual

visual angle of the far object with angle of the fixated object / one of the so called clues /.

These views of Helmholtz can be interpreted that the distance in the third dimension of the double images is not seen but estimated on the basis of some empirical factors / clues / in general and particularly on the basis of the sensation that the double images belong to one object. When this sensation ceases the double images become monocular images and then the estimates of their distance is effected on the basis of the same clues or factors as in the monocular vision.

According then to Helmholtz the monocular and binocular vision in double images is not three-dimensional in principle. We can only make estimates of distance on the basis of different non spacial but empirical factors like muscular efforts of accommodation and convergence, of comparison of visual angles, of sensations that some images belong to themselves or to one object - all this through t the association or as Helmholtz expresses sometimes through the so called unconcious inference.

Similar views were expressed by many workers in this field, among others by A. Tschermak and P. Hoefer 43/ in the paper : " Uber binoculare Tiefenwahrnehmung auf Grund von Doppelbildern " , which has been discussed before. 52/

C/ Accommodation and convergence.

The problem which of the factors : accommodation or convergence is more important in the depth perception was the subject of many experiments and theoretical disputes. The investigations carried out by Wundt 50/ the creator of experimental psychology in the early stages of his work in this field give an example of formulating the problem and drawing conclusion. These investigations are very instructive because of the faulty formulation of the problem and incorrect conclusions. In these experiments the person under test had to look first through a tube on a white screen limiting the field of vision. A black thread was introduced into this field and he had to look at it and remember its distance. Then he turned his eyes to the side and the thread was moved forwards or backwards. After looking again the observer had to say whether it was nearer or further away than in the previous position. Similar experiments were conducted with monocular as well as the binocular vision. The results have shown that the just noticeable differences in distance were much smaller in binocular vision than in monocular vision. In the case of monocular vision only the accommodation and in binocular vision convergence also were admitted by Wundt to be of importance, and he jumped to the conclusion that the convergence of the eyes has a much greater importance

importance for depth perception than the accommodation. It is to be noted that here the problem of the estimates of distance of fixated objects was investigated; Wundt considered that the influence of accommodation on the depth perception was due to the sensations of changes of accommodation of the eyes and not to the change of the character of the images formed on the retinas caused by the changes of accommodation. On the basis of these investigations and conclusions the controversy arose among the workers on the space perception [2,25]; while some stated that neither accommodation nor convergence had any influence on the depth perception, some followed the lines of Wundt and some others assumed that accommodation as well as convergence served as "clues" for distance in monocular and binocular vision.

The more recent investigations carried out by Vernon W. Grant [14] have not arrived at a definite conclusion in this matter, while William H. Ittelson and Adelbert Ames, Jr. [26] in the discussion of their investigations returned to the old ideas about the influence of muscular efforts of accommodation and convergence on depth perception, which they expressed as follows : " We cannot emphasize too strongly, that for our observers the muscular efforts of accommodation and convergence were related to a subjective change of apparent distance with all other things remaining constant."

D/ E. Hering's theory.

21/,22/,23/,24/
E. Hering, the eminent Austrian physiologist, tried to explain the phenomena of the depth perception in a different way from Helmholtz. With his name is connected the theory of the so called identical or corresponding retinal points, or otherwise the disparity theory. E. Hering in opposition to Berkeley and Helmholtz who were empiricists and associationists, belonged to the nativist school of depth perception which originated from Kant's philosophy. The second characteristic feature of Hering's theory is that it was based on the changes occuring in the peripheral sense organs and especially on the retinas. In the matter of identical retinal points Hering was a follower of Lotze's local sign theory. The starting point in building up his theory were the facts of stereoscopic vision in general and the Panum 35/,36/. phenomenon in particular, discovered in the first half of the XIX century. Hering formulated a theory of threedimensional vision based on the processes occuring on the retinas of both eyes without using as the means of explanation the different efforts and the muscular sensations of the eyes and of the body like the empiricists and the associationists. According to him every point on the retina has three local signs : one determining the vertical, the second the horizontal position, and the third the distance

distance in the third dimension. This last sign may have a positive or negative value and thus contributes in an algebraical form to the binocular perception of the distance. Let us consider for example the Panum phenomenon in its original form taking into the account the places on the retinas where the images are formed, thus we have two threads in front of the left eye and one in front of the right eye ; they are fused together by a stereoscopic process. If for example the left thread of the left pair coincides with the single thread on the right the images of these threads are formed on the identical points on retinas ; at the same time the right thread of the left pair forms an image on the temporal side of the left eye and is seen nearer than the other image. If on the contrary the right thread of the left pair coincides with the single thread of the right eye then the images of these two are formed on the identical points of the retinas and the image of the left thread of the left pair is formed on the nasal side of the left retina and it is seen further away than the other image. Hering generalises the results in stereoscopic vision on double images formed with normal fixation. All images formed on the corresponding points of the retinas are seen in the so called "Kernfläche" i.e. at the same distance as the fixation point. The images formed with some disparity or on opposite points of the retinas appear

appear outside their Kernfläche or at a different distance than the fixation point if they are seen singly. The same applies to the double images /Trugbilder/. The double images formed on the temporal sides of the retinas are seen in front of the Kernfläche or nearer than the fixation point, and the nearer the greater their disparity on the retinas / until a certain limit of disparity is reached / ; on the other hand from the so called Hering's Fallphaenomenon we learn that if the ball falls behind the fixation point the double images formed on the nasal points of the retinas are seen behind the Kernfläche and the further behind, the greater the disparity of the retinal images.

According to Hering we can define the distance in the third dimension of a point on the retina as its lateral distance from the central vertical line. We can define it as positive / seen further away / if it is situated on the nasal part of the retina, and negative / seen nearer / if on the temporal part of the retina. If the images are formed not on the corresponding points of the retinas but on quite opposite i.e. symmetrical points they are related to the perceptions of the same distance. This theory of Hering intends also to explain the perceived differences in the third dimension between the two double images. These differences result from the formation on the retinas of the images on the not symmetrical points

points. This last application of Hering's theory contains its main difficulties. If we fixate a point and place a lateral object so that it is seen in unilateral images i.e. in double images which appear on one side only of the fixation point,one of these images is formed on the temporal side of one eye, while the other on the nasal part of the other eye, and according to Hering's theory the first image should be seen nearer than the fixation point and the other one further away. Hering stated that in some particular conditions he can see this, but this perception is of short duration and very unstable. The authors previous investigations proved that there are positions of the object seen indirectly when this really occurs, but these cases are exceptional and subject to special conditions. Generally in the above described situation both unilateral double images are seen nearer or further away than the fixation point although there might be a difference of the perceived distance between themselves. These facts disprove the generalisation of Hering's disparity theory to the whole field of binocular vision and in particular to the case of the depth perception of double images. Hering's theory cannot explain either the relation between monocular vision and binocular vision in double images.

In spite of these deficiencies Hering's theory of corresponding points and disparity is widely

widely recognized and can explain the majority of the so called stereoscopic phenomena. Hering was the only author of the XIX century who tried to give consistent reasons, based on the physiology of the eye why we can see something nearer or further away or at the same distance. Many of his modern critics, for example those of the Gestalt school cannot offer plausible alternatives.

Hering stated that depth perception resulting from the disparity of the images on the retinas is not based on any empirical data, it is nativistic, but ~~there~~ that there are other experiences especially with monocular vision or the vision of distant objects, in which various empirical factors /among others size constancy/ can assist in seeing distance. This may help the primary depth perception, but sometimes they may also impair it. This second kind of experience can be called the secondary factors, clues, etc.

E/ Professor W.Heinrich's school.

Quite a different formulation of the problem was suggested by Prof. W.Heinrich[17,18] of Kraków /Cracow/ University. He writes[18]:

" The psychological problem of space became one of the most important subjects of philosophy after Descartes. Descartes could ask what was the foundation of our knowledge of distances in space. But when for

for the starting point the states of conciousness were chosen which consisted of sensations i.e. non spacial elements, the philosophical side of the problem as well as the psychological proved to be of importance. From the philosophical point of view the answer was to be given to the question how we arrive at the concept of space which comprises the whole physical world. From the psychological point of view one had to state how non spacial elements give rise to space perception. Both problems remained unsolved. Conciousness could not go beyond and create space outside itself. None of the psychological theories which tried to explain the formation of the threedimensional spaciality could accomplish this task . . . . "

" The analysis of what is an immediate datum is one of the subjects of psychological investigation. Consequently we do not ask how the spaciality is formed, but how it is given, and propose to analyse its elements. But this analysis is a very difficult problem. The continuous changes of the spacial dispositions given immediately are the foundations of different experiences and result in that generalisation which is the notion of space. This notion leads continuously from the synthesis of different experiences to the actual spacial perception given in one particular perception and makes us believe that the notion of abstract space is contained in it. One must however distingiush these two things. The notion

notion of space is an abstract concept in a form of space geometry and is a generalisation of the totality of our spacial experiences. These experiences allow us to determine various spacial relations, relative positions etc., they give us these relations which we know from geometry. The immediate space perceptions give us the spacial relative dispositions which we find at each look. This distinction gives rise to a series of questions concerning the relation between the geometrical dispositions and the immediate space perceptions ......"

" It was the traditional point of view that the monocular vision is only bidimensional. The three-dimensional space perception was the product of the binocular vision..... The most important proof of that was given by the stereoscopic phenomena in binocular vision. If we examine these phenomena we find only that depth perception is only reinforced but not formed by stereoscopic vision. It exists already in monocular vision."

The investigations on depth perception in monocular vision were the subject of papers by Heinrich[17/], Kurtz[29/], Loria[30/], Grzybowski[15/] and Zając[51/] /the author/. The general results can be formulated as follows :

"If we look with one eye through a tube /in order to obtain steady conditions of fixation/ at a point placed against a uniform background as a fixation point, the position in the third dimension of this

Fig. 1.

Fig. 2

this point if undetermined. But with relation to this point we can find a whole surface all the points of which do not present any difference of distance in relation to the fixation point. This surface is called the surface of reference. /Fig.1 represents an example of the horizontal section of this surface./ Every point placed within this surface is seen nearer than the fixation point, and every point situated outside this surface is seen further away."

"These facts prove that monocular vision is three-dimensional, and constitute a new starting point for further analysis. These findings are independent from all psychological consequences. Let us now introduce this point of view. In front of me I have a subject whose statements give me the relations previously described. On the other hand I examined the relation between the light rays starting from the points of the visual space an.. the eye of the subject. I examine the course of these rays through the lens and the different media of the eye, the images on the retinas etc. I ask myself whether I can establish a relation between the results of this examination and the statements of the subject. The following will be found : If the stabilization of the lens is obtained by the fixation of a central point in the surface of reference this surface is related to the retina in the following way : sharp

sharp images are formed on the retina of all the points placed geometrically on this surface. All the points placed inside or outside this surface form blurred images on the retina."

The author[51] has undertaken similar investigations on the monocular depth perception of points lying in the vertical plane. The establishment of curves both in the vertical and the horizontal plane all the points of which were seen equidistantly allowed the construction of a complete surface of reference for monocular vision of a paraboloidal form.

Further investigations by the author[52] led to the conclusion that the depth perception of the double images in binocular vision is based on the same principles as in monocular vision. This is illustrated in fig.2 where the curves of reference /L,R/ for both eyes are shown intersecting at the fixation point. We see that the point A situated outside both curves is seen in double images appearing further away than the fixation point. Point B situated on L and outside R is seen in the double images of which one is seen equidistant and the other further away than the fixation point. Point C situated on R and inside L is seen in the double images of which one is equidistant and the other is seen nearer than the fixation point. Point D between R and L is seen in the double images of which one is seen nearer and the other further away than the fixation

fixation point. Finally the point E situated geometrically nearer than both curves appears in the double images seen nearer than the fixation point.

The previous theories could not explain the depth perception of the double images because they could not related those phenomena to monocular vision. Our investigations resulted in findings which allowed us to establish this relation.

In all these investigations by Prof. Heinrich and his collaborators the subjects were always asked to state what was the relative distance of an object with respect to another object which was fixated, and in this way the curves and surfaces of reference were determined. The depth perception of the fixation point itself and the factors determining this perception were not the object of these investigations. It can be said that an isolated point in the visual field is seen somewhere in space but its distance from the eyes cannot be determined. All the geometrical constructs /e.g. the intersection of the visual axes/ are theoretical arguments which cannot be an object of immediate perception. Also the analysis of the physiological or psychological attempts to explain the depth perception of fixated objects, like effort of accommodation and convergence, oscillation of the attention, etc. seem to prove that the location in depth of the fixated objects in monocular as well as in the binocular

binocular vision is rather a problem of estimates than of seeing in depth. On the contrary when we have a fixation point or object we can determine the relative distance of points situated laterally : we see it. The results of our investigations have determined the character of the spacial orientation in the monocular as well as the binocular vision of the double images. The respective curves and surfaces of reference are not seen at a determined distance. They only represent the geometrical loci with respect to which the spacial orientation in the third dimension exists. These surfaces constitute the relation between the geometrical constructs and the depth perception phenomena.

Let us now pass to the physiological side of the problem. If our investigations are made within the range of accommodation of the eyes the sharp images of the fixation points are formed on the retinas ; this is the result of the fact that the focal line which in this case is reduced to one point coincides with the retina /fovea/. The images of the points situated laterally are the astigmatic images which become circles or ellipses of dispersion greater or less depending on the angle between the visual line and the visual axis and the geometrical distance between the lateral point and the fixation object. In the case of the astigmatic images two focal lines are formed. The position of the first focal line is according to our

our hypothesis the decisive factor for depth perception. When it coincides with the retina - which is related with the fact that the corresponding point is situated on the surface of reference for monocular vision - we do not see any difference in distance between the lateral object and the fixation point. When this focal line is formed in front of the retina - in which case the corresponding point is situated geometrically behind the surface of reference - we see the point further away than the fixation point. When the point is situated geometrically nearer than the surface of reference and consequently the nearer focal line is formed behind the retina, we see this point nearer than the fixation point. We can conclude that accommodation plays its part in depth perception because it determines the situation of the focal lines with respect to the retinas. We speak here of the relation of the accommodation of the eyes to depth perception in a quite different sense from those who supposed that the sensations and muscular efforts of accommodation are the constructive elements of the depth perception. Accommodation does not act immediately ; the sensations of the accommodative efforts do not help to create depth perception. But each state of the dioptric apparatus of the eye determines the optical character of the images on the retinas and the character of these images is related to the depth perception of the

the corresponding objects seen indirectly.

f/ "Gestalt"theory.

Quite different and new views on depth perception are expressed by the Gestalt school [28/47/48/] of psychology. These views are naturally influenced by their general principles, some of which, necessary for the understanding of their views on depth perception will be given below.

First of all this school admits the existence of some dynamic forces which operate in the organism and bring some organisation in what is perceived. Perception is not a copy of the stimulus, but results from the interaction of the properties of the organism. For example a three dimensional stimulus gives only a twodimensional image on the retina, yet the organism has the capacity under certain normal circumstances to reconstitute the three dimensionality in the perception. While it remains true that the retinal image is the primary basis for the perception of visual form, ~~neither~~ nevertheless it can be shown that many of the characteristic features of perception are added by the central nervous system, some of them determined not by the stimulus but by the organism, its attitudes and its past experience. Although the retinal image is bidimensional this image is propagated to the optical centre in the brain which itself is threedimensional

threedimensional, and so our perception becomes also threedimensional.

The first feature of the Gestalt school is that under the simplest conditions of stimulation our perception is threedimensional. In this the Gestalt theory of the depth perception is nativistic like that of Hering.

The dynamic forces which can organize our field of perception are numerous and of various kinds. One of them was introduced by Szuman[39] before the Gestalt theory, Namely the attention which constituted the force of binding, for example, the parts of a figure into a whole, so that the total impression instead of some of its parts became effective. If we look into a field of vision a figure attracts more attention than the background which occupies the rest of the field, and the figure appears nearer than the ground even if both were placed in the same plane. The figure acts as a whole and being an object tends towards constancy.

This kind of speculation about the forces operating in organizing the perception is called the field theory. /The expression used by the followers of the Gestalt school perhaps in a sense analogous to the concepts of magnetic and electric fields where the appropriate forces are operating./

There are different dynamic factors which influence

influence our field of perception. In the following only those are mentioned which have any bearing on space perception.

" One of these is the law of the dynamic basis of form. A form is a dynamic system or is based upon a dynamic system. Since the dynamic principles operate within the organism a strong form is one which depends more upon the dynamic properties of the organism than upon the properties of the stimulus. The fact that the organism operates to structure the perception means that there need be no close correspondence between the form of the stimulus and the form of the perception. Thus for example, the stereoscopic images are more stable than double images or ~~the~~ monocular ones, although they do not correspond to the stimulus ; they result from the forces operating in the nervous system."

There are other Gestalt laws like the law of figure and ground, the law of the integration of similar and adjacent ; one of the most important in connection with depth perception is the law of constancy, also the law of the tendency to build objects from points or lines is of importance here. This dynamic law explains according to the Gestalt theory the stereoscopic phenomena resulting from looking at plane figures.

The Gestalt school critisizes the theory of disparity in ~~the~~ depth perception. Koffka writes[28] :
" We are far from denying the importance of binocular

binocular parallax as a cause of threedimensionality, but"......"we shall prove it to be the cause of forces of organisation which may either cooperate or conflict with other forces of organisation. I should also be very wary in denying that experience has any influence on depth. Only before we know what experience means, the introduction of experience has no explanatory value and only when we understand experiece as a process of organisation itself will it help us in our present problem." ...... " OUr main claim is that there are other forces of tridimensional organisation than binocular parallax, forces that may be stronger than this last factor."

" What we shall try to do here is to show that retinal disparity is a factor of organisation depending upon organisation. The traditional treatement of this factor consists in describing the facts without any attempt at going behind them. Corresponding points are defined as points which when simultaneously stimulated give rise to the perception of one object, or as point the stimulation of which gives rise to the perception of one and the same direction. Then the statement is added that if one and the same spacial point is projected on two noncorresponding retinal points it will appear double except when the amount of disparity is small : in that case the point will be seen as one but either in front or behind the plane

plane of the fixation point the "nuclear plane" /Hering's Kernflache/ according to the direction of disparity. Why disparity has these effects is either not stated at all often because it is assumed to be such an ultimate fact as that stimulation by long wave light gives rise to the sensation of red, or is treated in such general terms "utilisation of a distance cue by the organism" that the student is in reality no better off than in the first case. The facts of retinal disparity as usually stated are facts of geometry. What we require are facts of dynamics. We want to know the forces which result from the geometry of disparity."... ..." Supposing I chose the point X_l on the left retina and find the point X_r on the right retina which corresponds to it ; how can I express the result of this process without using the word corresponding ? One might try to accomplish this by saying : when two corresponding points are stimulated in the same manner then the result will be the perception of one point in the "nuclear"plane". The equality of stimulation would be required for the definition of correspondence i.e. something which transcends pure geometry."

"What is true of corresponding points is equally true of disparat ones. To say that Y_l is disparat to Y_r means that when these two points are equally stimulated the result will not be the perception of one point in the nuclear plane - but either of two points or of one point not in the nuclear plane"......

......" Such stimulation will as a rule result in depth relief, indicating the disparate points determining the effect. That means ; which pairs of points or lines on the two retinas will cooperate in determining the perceptual organisation depends upon the two retinal patterns. This is not a geometrical or anatomical fx but a dynamical fact. In each case there must exist real forces which lead to one kind of coordination rather than another. The immediate origin of these forces cannot lie in the retinal patterns themselves since they are separate and therefore unable to interact. Interaction can take place only where the processes started in the two optical tracts by the retinal patterns converge in the brain. These prcesses will interact according to their structual properties i.e. figure will interact with figure and the ground with ground and not vice versa ; a unique point in a curve will interact with the corresponding unique point in the other curve, whether they are projected on identical retinal points or not and so forth. In other words the very concepts of corresponding and disparate points presuppose the concept of organisation."

This applies to the experiment with points shown in the figure above and seen stereoscopically. Only

"Only the points F_l and F_r are projected on identical retinal points while the other two cannot fall on identical points if F_l and F_r do. They will however interact ; being two figures in close proximity they will attract each other, their union being prohibited by the union of the two other points. But there is no reason why P_l should interact with P_r which belongs to the background, or P'_r with P'_l. In the " combination zone" , as I have called that part of the psycho-physiological field where the processes started in the two eyes combine, a <u>stress</u> results when the conditions are of that kind of which our experiment with two pairs of dots is the simplest example. We now introduce the assumption that provided the disparity is not to great, this stress results in the unification of the two attracting points and at the same time in depth relief, one single point appearing either nearer or further than the other. This hypothesis is consistent with our whole treatement of perceptual organisation, since it attributes a definite effect to definite forces. It is incomplete because it cannot deduce why this stress which according to its nature should lead to unification of the points P_l P'_r cannot be of the same kind as that between F_l F_r since the latter reduces the stress in the field to a minimum while the former creates stress and that the only possible difference between the two unifications in pure spacial form is a difference in depth."

Another author of the Gestalt school Prof. Wilde[48] proposes to eliminate the theory and conception of disparity as a concept based on physiological happenings on retinas only and replaces this by a Gestalt concept of Gestalt differences; he also defines as a Gestalt function which can be applied to the stereoscopic phenomena the "Mitnahme" /attraction/ in the same sense as given by Koffka.

In general the Gestalt theory of space perception is based on the following :

a/ the field concept,

b/ the dynamic forces operating in this field : among others similarity law, object forming law, attraction /Mitnahme/, stress law, etc.,

c/ the introduction of the central nervous system for explaining depth perception,

d/ the concept of isomorphism,

e/ nativism.

Convergence and accommodation lose in this theory much of their importance. Although it is known that convergence alters the perceived distance and size, that result might come from the corresponding alteration of retinal disparity.

I do not intend to critisize here the Gestalt theory in general, but only to stress that :

1/ the not clearly defined dynamic ~~forces~~ factors

factors do not give a better explanation of the phenomena than all cues, unconcious inferences or other factors used until now.

2/ This theory can be interpreted as explaining the fact that we see something at different distance than the nuclear plane, but it cannot explain why we can see sometimes nearer and sometimes farther away, why attraction or Mitnahme operates in one and not in another direction which is essential for every theory of depth perception.

3/ The Gestalt psychology has not given any satisfactory answer to the problem of relation between the monocular and the binocular vision of depth.

G/ The problems of the so called "clues".

When the problem of depth perception arose various authors tried to answer different questions connected with it. One of the first questions was : Is the depth perception something innate or something acquired by experience ? If it is something innate /as according to the nativistic school of space perception/, then what are the facts and the primary data of depth perception, how are they related to the reality of the third dimension /geometrical relation/, and how are they related to the changes occuring in the sense organs /peripherial and central/ ? Apart from seeing

seeing in the third dimension there are other facts concerning not the perception of depth but the estimates of distance of objects ; in this case the distance is not seen but may be estimated. If so, even the nativistic must ask what are the different factors determining the estimates of distance. A further question put by this school was that if these factors determining the estimates of distance might also have some influence on the first category of facts that is of seeing in distance; they might help seeing in distance or impair it, or in general change the perception of distance in some way.

The second school of thought about space perception was that of empiricism. It generally ascertained that the perception of distance is aquired by experience. Apart from answering the same questions which the nativistic school had also to answer about the factors on which the estimates of distance are based they had in the first place to solve the problem how from perceiving only in two dimensions we can arrive at seeing in the third dimension ; which are the factors responsible for depth perception and what part they play in it. Various attempts to answer those questions led to the formulation of some factors which were called "clues" or "cues". The most important of them are : Convergence in the geometrical sense and as muscular sensations, accommodation both in the optical sense and as muscular effort, the changes in the size and

and shape of pupils, the size of objects, linear and aerial perspective, overlapping of objects in the visual space, the brightness, the distribution of light and shadow, distinctness in general, distinctness of outlines in particular, the situation of objects in height, parallax displacements with movements of head, binocular parallax, form of the objects, and tensions accompanying different forms, the differences in the colouring, the double images, the distribution and oscillation of attention, the movements of the objects, the movements of the eye /eyes/, disparity on the retinas. These clues can be divided into several groups :

1/ visual clues in stationary condition : size of objects, linear and aerial perspective, overlapping, brightness, light and shadow, distinctness, situation of objects in height, binocular parallax, form of objects, differences in the colouring, the double images,

2/ visual clues resulting from movements : parallax displacements by movements of the head, the movements of objects, the movements of the eye /eyes/,

3/ other sense clues : muscular sensations accompanying convergence and accommodation of the eyes /eye/, muscular sensations accompanying the movements of the body in order to reach distant objects,

4/ clues resulting from different physiological processes which are not subject to immediate perception like the accommodation, the convergence, changes in in pupil, correspondence and disparity on the retinas,

5/ clues resulting from geometrical constructions : convergence angles, visual angles, perspective, projection of retinal images,

6/ clues resulting from psychological factors like experience in general, learning processes, associations of different kinds, tensions and stresses accompanying the incongruities of different forms, the distribution and oscillation of attention, etc.

It is very interesting to note which of these different factors were thought to "create" depth perception and not only to possess some influence on the already existing depth perception. Some authors like Berkeley[3/] and Helmholtz[20/] supposed that the association of the muscular sensations with the geometrical distance created the depth perception. The convergence of the eyes in the sense of the geometrical clues was considered as a very important factor. The disparity of the retinal images was regarded by several authors as a creative factor of depth perception especially in the case of stereoscopic vision. Helmholtz asserted that the double images, if they are not to far apart from each other, determine the depth perception of the corresponding object seen indirectly and Woodworth[49/] even stated that the double images are excellent cues of distance because we know that the crossed images belong to the nearer and uncrossed to the further objects than the

the fixation point /in reality we cannot distinguish which images are crossed and which uncrossed without closing one eye/.

Different answers are given to the question how this creation of the third dimension can be achieved : some association process or some kind of unconcious inference? But in all cases the answers are insufficient and we cannot be satified with those theories which cannot explain how the two dimensional perceptions or elements can create the spacial depth perception, how an association of one kind of sensational perception to another not yet in existence can create this last one.

There is also another meaning of the so called clues. If we assume that depth perception is an immediate datum or fact, there may exist some factors which would help or interfere with it. This may apply to seeing in third dimension as well as to the estimation of distance of objects in our visual field. This kind of interpretation of the clues arose from Leonardo da Vinci's 46/ endeavour to formulate the principles of ~~the~~ linear and aerial perspective, use of light and shadow, and of colours, which could help the painter to represent the third dimension in nature in the twodimensional medium of the picture. This meaning was also given to such factors as size, overlapping, distinctness and blurredness, which help to estimate which ~~are~~ objects

objects are nearer and which further away. This kind of association between the one kind of sensations and another /already existing perceptions of distance/ can be established and function. In the same sense only the role of experience can be investigated and determined.

There is still another meaning which can be given to the so called clues. This meaning was given when the depth perception phenomena were investigated, and the attempts were made to establish the relations occuring between the visual phenomena on one side, and the corresponding geometrical constructs, or the processes occuring in the sense organs /peripherial or central/, or between the space perception phenomena and other psychological data like distribution of attention etc. But in this case the meaning of the word clues has no sense at all. We can for example investigate how different objects placed in some geometrical disposition are seen in the third dimension by the observer in various conditions of fixation, brightness, colour, distribution of attention, etc.; we can also investigate how different states of accommodation, different characteristics or deficiencies of eye organs are related to the phenomena of depth perception. This kind of relations were investigated by Prof. Heinrich and his collaborators. The experiments on the differences between the monocular and the binocular depth perceptions are of the same kind.

Only the second conception of clues may retain its

its name. In the other cases the word clues cannot be logically applied.

Different authors atributed some clues to monocular and some to binocular vision. Many tried to biuld some hierarchy among them, stating which are more, which are less important , which are primary and which secondary, which are cooperating and which conflicting [5, 9, 10, 41, 49]; many experiments were conducted with object to determine their influence on the depth perception.

One of the workers in this field, M. D. Vernon [44] in his paper "The perception of distance" concluded that the most essecial feature of the processes of distance perception and estimation was the visual perception of a threedimensional configurational structure with which were closely correlated the perceived perspective form of the general setting and surroundings /and the inter-relationship of its constituent parts/ and the graduated series of impressions of disparity, size, clearness, "insistency" and brightness.

Yet another answer to the question, what is the meaning of clues and their relation to the perception of distance was given by James J. Gibson [13]. He introduces a conception of retinal gradients as variables of stimulation, and by means of this conception he generalizes the different kinds of disparities described till now as various kinds of cues. "The word gradient means nothing more complex than an increase or decrease of something along a given axis or dimension." The

The gradient might be positive, negative or zero. He applies this conception of gradients to different elements related to the perception of distance and classifies the so called clues under two principal headings : 1/ those of which the gradients constitute the stimuli for distance, and 2/ those which are not stimuli but rather indicators, or signs of distance, and which thus can retain their name and meaning as cues. For example he writes : "One might speculate that variation in hue or shading as such do not produce the same compelling impression of depth that gradients of texture, line, size, binocular disparity, and motion produce, just because they are not related to physical depth by geometrical laws as the latter. Variations in hue and brightness can and do produce compelling experiences of outline, form, and pattern in the two dimensions of extensity, but their correspondence to experiences of solidity, depth and distance is less precise." Also the blur occuring when the eye is not properly accommodated on an object cannot according to Gibson be considered as an effective, independent stimulus for distance. One of the reasons for that is, that the gradient of blur cannot assume positive and negative values, as do other gradients which constitute the real stimuli for distance. One of the most important stimuli for distance is the gradient of texture of surfaces which is a stimulus for continous perception of distance. Binocular gradient of disparity is for

for Gibson one of several even in stereoscopic vision and the emphasis on it as cue for depth has been in his opinion much exaggerated. He is undecided, whether the gradient of light and shadow should be considered as stimulus for depth or not. In the summary of his analysis eight of the thirteen cues for depth listed by him can be thought of as stimuli for perceptions of space. The remaining five are better conceived as probable signs, secondary ones, or as having doubtful status.

II

EXPERIMENTAL INVESTIGATIONS AND THEIR DISCUSSION.

A. Relation between the depth perception and changes of fixation point for indirect monocular and binocular vision of double images.

The present investigations are the continuation and developement of experiments on visual space perception carried out in the Laboratory of Experimental Psychology in Cracow University, Poland.

The starting point to this part of investigations was the following observation made by the author and described in the paper "La localisation en profondeur des images doubles" 52/ :

" If we place ourselves in a room with the back near the window and facing the opposite wall and fixate monocularly a point on this wall we perceive a certain spacial disposition of different objects in the room and on the wall itself. This wall has some dimensions and is seen at some distance from us. If now we fixate a point situated at a much smaller geometrical distance from the eye we observe the following ; the dimensions of the opposite wall are seen much smaller in comparison

comparison with those seen before, and we see this wall at a greater distance ; we have the sensation as if the whole room became longer and narrower at the same time. If we move the fixation point from near the eye towards the opposite wall continuously and slowly enough so that the eye could steadily accommodate on it we observe the steady diminution of the distance of the wall and the increase of its dimensions. When we displace the fixation point in the opposite direction we perceive the opposite phenomenon i.e. the increase of the distance and the diminuition of the dimensions of the wall and of other objects situated behind the fixation point."

"This phenomenon is striking especially in the case of objects situated behind the fixation point, but it is also observed with the objects placed geometrically in front of the fixation point provided that the latter is situated at a comparatively great distance from the eye ; if this distance was small I could not observe this phenomenon. We could not also observe these phenomena when the investigations were carried out beyond the sphere of accommodation of the eye for fixation points. For the eyes of high degree of myopia this phenomenon does not take place even for small distances between the eye and the fixation point."

The investigations described in the present paper were made with the object of veryfying these data and exploring what happens in the case of double images

images formed with binocular vision.

1.

The present investigations were carried out in a long narrow room of 41 ft. by 7 ft. There was a window at the end of the room and a glazed door at the opposite end. This door was illuminated by a side light. The subjects were placed near the window and looked in the direction of the door.

Two series of experiments were carried out.

The first series was as follows :

The subjects first fixated with one eye a small ball 6 mm. in diameter supported by a rod placed as near the eye as the accommodation would allow /about the near point of accommodation of the eye/ and at the same time without changing the fixation point they paid attention to the rest of the room and especially to the opposite door. Then they moved the fixation point from near the eye to a distance at arms length observing at the same time the changes in the distances and dimensions of the door and the objects in the room. They were asked what observations they made about the changes in sizes and distances of the room and the door. The fixation point was then moved back towards the eye and the corresponding observations were made. The same experiment was carried out with the other eye, and then also by fixating the ball with both eyes. In this last case one observed the changes in the double images of the room and the door.

Thirteen persons took part in this first series of experiments. Eleven have fully confirmed the results for the monocular space perception given previously. But not all phenomena were observed simultaneously by all the subjects. For example, one perceived the change in the distance of the door, the change in the width of the room, but did not observe the change in the dimensions of the door. Another did observe the change in the distance and size of the door, but not in the width of the room. Certain persons observed the changes better with one eye than with the other, which could be attributed to the difference between the eyes. The discrepancies mentioned above might be ascribed to the fact that the persons were making observations of this type for the first time. When the same subjects came to the second series of experiments these small discrepancies mostly disappeared. Only two persons could not observe clearly the phenomena, but on no occasion were the observations contrary to the results stated above.

The results of observations with double images /binocular/ were quite similar to those with monocular vision. This confirmed among other things the hypothesis postulated in the previous paper i.e. that the double images in the binocular vision are seen in three dimensions as are seen the corresponding single images in monocular vision.

But it must be mentioned that on account of the overlapping of the images in this case the vision of of the whole room was rather blurred and not so clear as in the case of monocular images and in consequence rather more stress was laid on the observations of the changes in the distance and the size of the door. These double images of the door were seen larger and nearer when the fixation point was further from the eye, and the opposite was observed when the fixation point was nearer to the eye. This was observed by eleven people out of thirteen. One must also add that similar changes occuring in the vision of the whole room were observed by several subjects. No observations contrary to the hypothesis were made.

In the second series of the experiments the subjects were asked to make the following observations :

1/ What changes did they observe when steadily moving the fixation point away from near the eye and back.

2/ During which part of this movement the changes were more pronounced.

3/ What changes did they observe in the size and the distance of the door when they changed the fixation point from the furthest position of the ball to a fixation point on the door itself.

4/ What differences, if any, did they observe between the two double images concerning size, and distance during 1/ and 2/.

1/, 2/ and 3/ were carried out first with one eye

eye, than with the other eye, and afterwards with both eyes. Eight persons out of the previous thirteen took part in this second series of experiments.

The following results were obtained :

Ad 1/ All the persons stated that during the steady movements of the fixation point they observed steady changes in the width and the length of the room, and in the size and in the distance of the door, i.e. the increase of the width and the decrease of the length of the room as well as the increase of the size and the decrease of the distance of the door during the movement of the fixation point away from the eye. Reverse changes were observed during the movement of the fixation point in the opposite direction. In the case of the binocular vision they observed better the changes in the size and the distance of the door than the changes concerning the whole of the room.

Ad 2/. Some of the subjects in addition to the general observation of the steady changes could also observe when the changes were more pronounced. Some said that the changes were more pronounced while they moved the fixation point away from the eye, others observed the reverse phenomenon. Some observed more pronounced changes while moving the fixation point within a region near to the eye, others while they moved the fixation point within a region more distant from the eye. Some observed the phenomena better with one eye than with the other.

Ad 3/. Here also quite a variety of observations was obtained. Some of the subjects did not observe any changes in the size and the distance of the door when changing the fixation point from the ball at arm's length from the eye to a point on the door itself, or could only observe very insignificant changes. Others, on the contrary, could see appreciable changes. To the first category belonged mainly those who in the second part of the experiment observed more pronounced changes while moving the fixation point within a region near the eye /eyes/. To the second mostly those for whom the changes were more accentuated when moving the fixation point within a region more remote from the eye. In the case of the binocular vision all the subjects observed naturally the coming together of the double images of the door when they changed the fixation point from the ball to a point on the door itself. Most of them could also observe that now they could see the door more clearly than in the case of double images when the fixation point was in the previous position.

Ad 4/. Several persons observed a difference between the double images. For some of them it was only a difference in clearness. One of them observed a slight difference in the distance between the two images.

2

I want to stress here the fact that the changes

changes described above were actually <u>seen</u> by the subjects and consequently they have the value of <u>immediate primary data</u>. They were not observed as results of some kind of inference from other data. Neither they were estimated of sizes or distances. They had a character of something real and not of an "illusion". Most of the subjects confirmed that impression on their own accord and thought these experiences striking and unexpected. Only one person expressed some doubts as to whether his observations were inferred or not although he also confirmed the fact that he has actually seen the changes concerned. Not a single person has said that the changes observed could be a result of a comparison of the size and the distance of the fixation point with the other object seen indirectly. Several persons confirmed on their own accord the continuity of the changes in the third dimension as contrary to the momentary changes occurring for example in the cases of the "depth illusions". They have not found any fundamental difference between what they have observed monocularly and what they have seen binocularly in the double images.

Helmholtz[20] in a similar observation noticed only the changes in size of objects viewed indirectly. Here is a description according to Helmholtz of this phenomenon : "If the double images are very distant laterally from one another when a very near object is fixated - then when one cannot know that they belong

belong to one object, the binocular depth perception ceases altogether ; we can in this case as in monocular vision compare the visual angle of the far object with that of the fixated object : the linear size of the fixated object is known, it becomes automatically the measure which is also applied to image of the far object. Let us look for example at the house on the other side of the street fixating at the same time one finger placed in front of the eyes ; in this case laterally very distant double images of the houses will be seen. These images will increase in size when the finger is moved from the face away and decrease when the finger is moved towards the eyes. In the first case, as the visual angle of the finger decreases in relation to it, the visual angle of the houses increases and the finger serves as a fixed measure since its linear size and its distance are constantly perceived distinctly, which is not the case for the houses seen far away."

But we must note that this phenomenon is also observed when we do not fixate any material object, but if we are able to change the accommodation of the eye without any material fixation point, which is possible after some practice. This disproves Helmholtz's explanation /interpretation/ of size "illusions", as in this case there is no object which can serve as measure.

Herring[21/] observed not only the changes of size but also the "illusions" of depth. He writes : "When I stand in front of a large mirror so that I can still

still reach it with my hand and than close one eye and place my hand between the other eye and the image of my face in the mirror than I see this hand becoming bigger and smaller according to whether I move it between my face and the mirror towards the eyes or in the reverse direction, while I look at the image of my head covered partially with my hand. But when I direct my attention mainly to my hand while at the same time paying only a slight attention to the image of my head in the mirror then the head looks not as becoming smaller but as moving away from the mirror during the movement of the hand towards my eyes ; during the movement of the hand towards the mirror, the image of my head is coming towards me. But these observations can be made only when the attention is highly concentrated in order that it should not become wrongly divided."

Neither Helmholtz's nor Hering's observations were complete since both these phenomena i.e. the changes of size and of distance occur simultaneously.

Harvey Carr in a paper "A study of certain relations of accommodation and convergence to the judgement of the third dimension" 8/ has discussed the case of Miss Jessie B. Allen, Ph.D. 9/ who could locate the image of a fixed object at will, i.e. had the ability of voluntary control of depth location. For instance a house could be made to approach or recede at will. At least some of the experiments described in that paper especially in monocular vision might have the same significance as as the phenomena described in this paper.

All the changes observed here occured when the changes of the fixation point were made i.e. when the changes in the accommodation of the eye /eyes/ took place. So the correlation between the accommodation of the eye /eyes/ and the visual space perception was again confirmed.

The change occuring when the double images are formed by binocularly fixating a point are principally the same as in the case of the monocular vision. So it may be accepted that this phenomenon occurs according to the second principle, that the visual space perception of double images in the binocular vision is principally the same as in the case of the monocular vision.

The results obtained do not concern the differences which exist between the space perception in the monocular and the binocular vision of objects when they are fixated i.e. in direct vision.

The investigation described here gave so far only qualitative results but they must be regarded as fundamental data which every theory of the visual space perception must take into the account. Further investigations conducted on the same lines might result in :

a/ establishing quantitative relation between the changes in the visual space perceptions and the changes in the accommodation of the eye /eyes/,

b/ in working out some methods of measuring

measuring different characteristics of the eye /eyes/ as acuity, amplitude of accommodation, anomalies like astigmatism, different kind of ametropia, also differences between the two eyes etc.

B. Influence of colour on depth perception.

The main results obtained by Prof. Heinrich and his collaborators in investigations on visual space perception were that the vision in the third dimension was principally correlated with the accommodation of the eyes ; according to them and to the fact that the accommodation must depend on the refraction of the light rays in the eye the author proposed the hypothesis that the vision in the third dimension should be different for different colours.

Dr.M.Boniecka 4/ carried out experiments based on this hypothesis which resulted in tracing the curves for different colours,representing the loci of points where objects were seen equidistant with the fixation point. Her main results were that with a black fixation point the curve for red was situated nearer to the eye, than the corresponding curve for black, while the curves for green and blue were situated further away. These results were rather unexpected because on the basis of the Matthiessen formula discussed in Dr. M.Boniecka'S paper one should expect exactly the opposite results.

The present investigations were conducted in three directions :

a/ the determination of near points of accommodation of the eyes using different colour filters in monocular vision,

b/ the determination in monocular vision of the points seen at the same distance from the eye as the fixation point viewed always through a "Q" /non coloured/ filter while changing the coloured filters through which another rod placed laterally was seen indirectly. The different colours were : red, yellow, green, blue and violet.,

c/ observations on the differences in the depth perception of double images seen through different colour filters.

1

The following technique has been used for all these experiments.

The visual field was restricted by a white screen. The subjects looked through a rectangular slit 8.2 cm. by 1.2 cm. The colour filters were placed over the slit. Grey metal rods of 2.75 mm. in diameter were used as the observed objects. The field of view was illuminated partially by daylight coming through the window behind the observer, and partially by a 100 watt electric bulb placed 120 cm. above the slit. This was done to ensure uniformity of illumination, and the whole resulted in a yellowish background.

In the investigations on near points of accommodation the person under test looked through the slit monocularly and had first to determine the near point of accommodation without any filters. As a near point of accommodation was accepted the nearest point at which the rod was seen quite distinctly, not blurred, and without any shadows or parallel lines. This was determined by moving the rod towards the eye and away from it noting the points where the rod began to be blurred and again when it was seen quite distinctly. This was repeated several times. Near points of accommodation using different colour filters were determined in the same way.

The investigation on monocular vision was conducted as follows : The fixation rod was placed in the middle of the visual space ; in fixating this rod another rod placed laterally was moved until it appeared the same distance from the eye as the fixation rod. /This rod was placed some 4 to 5 cms. of lateral distance from the fixation rod. The lateral distances in figs. 5 and 6 are not the real ones, and the differences for different colours were given only for clearness of presentation./ The fixation rod was viewed through a "Q" filter and the lateral one through a colour filter simultaneously.

For experiments on double images the following procedure was adopted. First the preliminary adjustments were made without using any colour filters. Two rods

rods were placed one behind the other in the median visual plane. The nearer rod was fixated and the further one was thus seen as a double image. The further rod was displaced laterally until its two images were seen equidistant lterally from the fixation rod. Keeping the further rod in the same position the person under test was asked whether he /she/ observed any difference in the distance from the eyes of the two images. Both these observations were very important because the interpretation of the results was based on them, and for this reason they were checked several times during the experiments. Care was also taken that the position of the head of the observer should remain unchanged throughout.

The distance from the eyes of the nearer rod was about 20 cm. and that of the further rod 30 to 40 cm. and both were placed within the ranges of accommodation of both eyes for white light i.e. both were seen quite distinctly when fixated binocularly or monocularly.

When in this way the positions of both rods have been determined, different colour filters were placed in front of each eye and the subjects observed which of the double images / left or right/ was seen nearer to the eyes. They were also asked to observe which of them was seen nearer to the centre, i.e. the fixation rod, which was seen more distinctly, and which appeared to be thinner. All these above mentioned differences occured but there were also cases that no such differences

differences were observed.

In the cases when the nearer rod was fixated one dealt with the so called uncrossed double images /the right one bolonged to the right eye and the left one to the left eye/ ; when the further rod was fixated the nearer rod was seen in the so called crossed double images /the left one belonged to the right eye, and the right one belonged to the left eye/.

Two series of experiments were carried out on depth perception of double images by fixating the nearer rod and using different colour filters.

The first series consisted of using a "Q" filter /white light/ in front of one eye, and in front of the other eye one of the following colour filters : red, yellow, green, blue, and violet.

The second series consisted of using different colours in front of each eye.

In the first series there were ten colour combinations and twenty in the second.

In all the investigations only those perceptions were taken into the account which took place in a short time as first impressions, because prolonged looking was generally accompanied by different cases of inversions, image disappearances and other phenomena resulting from fatigue, eye rivalry, colour mixtures, etc.

Different kinds of Ilford colour filters were used ; the types of tricolour and mercury proved best suited for the majority of the observers. The correspon-

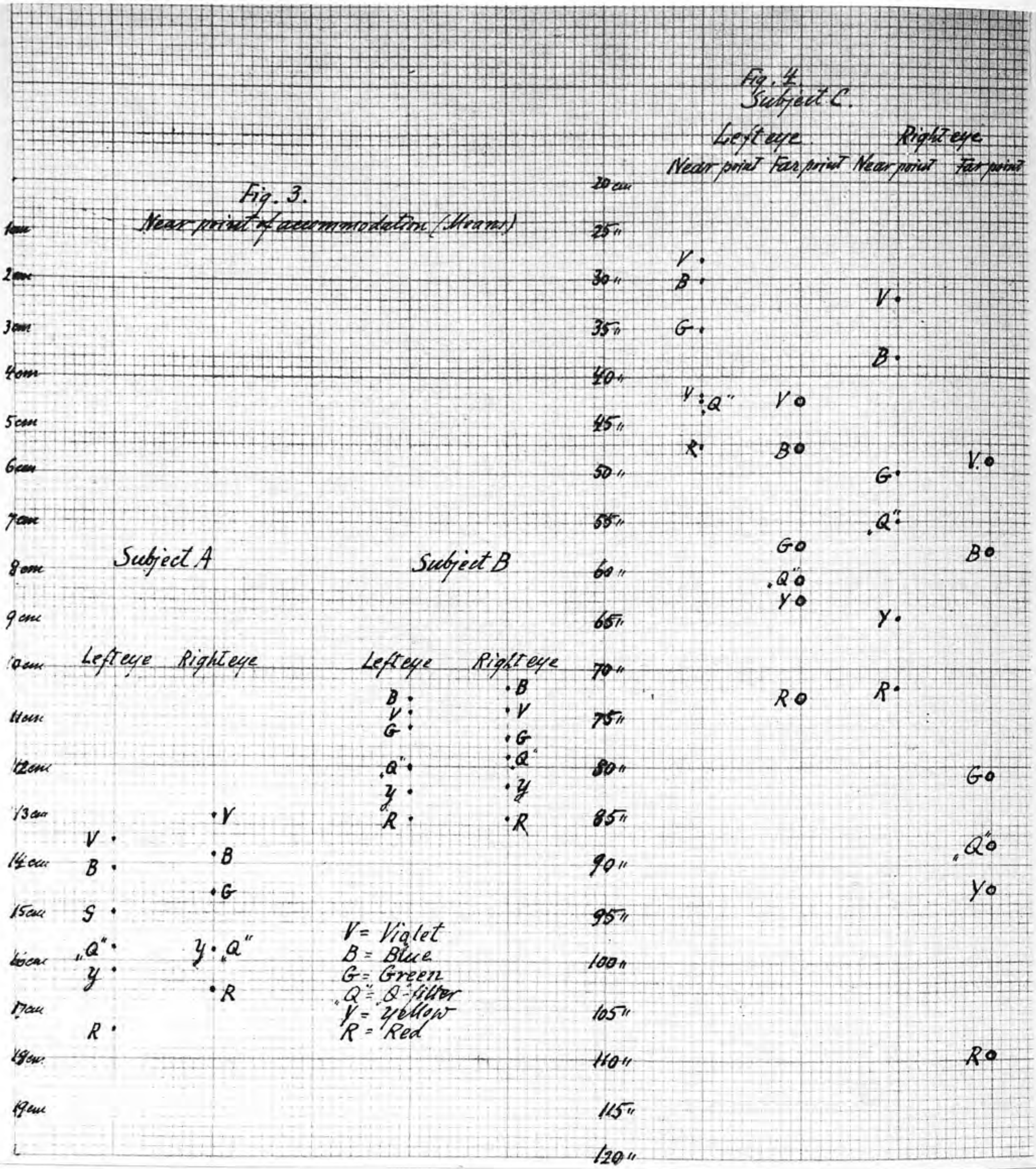


Fig. 3.
Near point of accommodation
Subject A
Subject B
Left eye
Right eye
Fig. 4.
Subject C.
Near point
Far point
V = Violet
B = Blue
G = Green
"Q" = Q-filter
Y = yellow
R = Red
1cm
2cm
3cm
4cm
5cm
6cm
7cm
8cm
9cm
10cm
11cm
12cm
13cm
14cm
15cm
16cm
17cm
19cm
20 cm
25"
30"
35"
40"
45"
50"
55"
60"
65"
70"
75"
80"
85"
90"
95"
100"
105"
110"
115"
120"

corresponding wavelengths of the filters used are shown in table I.

2

The results of the investigations on near points of accommodation are shown in the figs. 3 and 4. Two persons were tested more thoroughly, while a few others were examined occasionally.

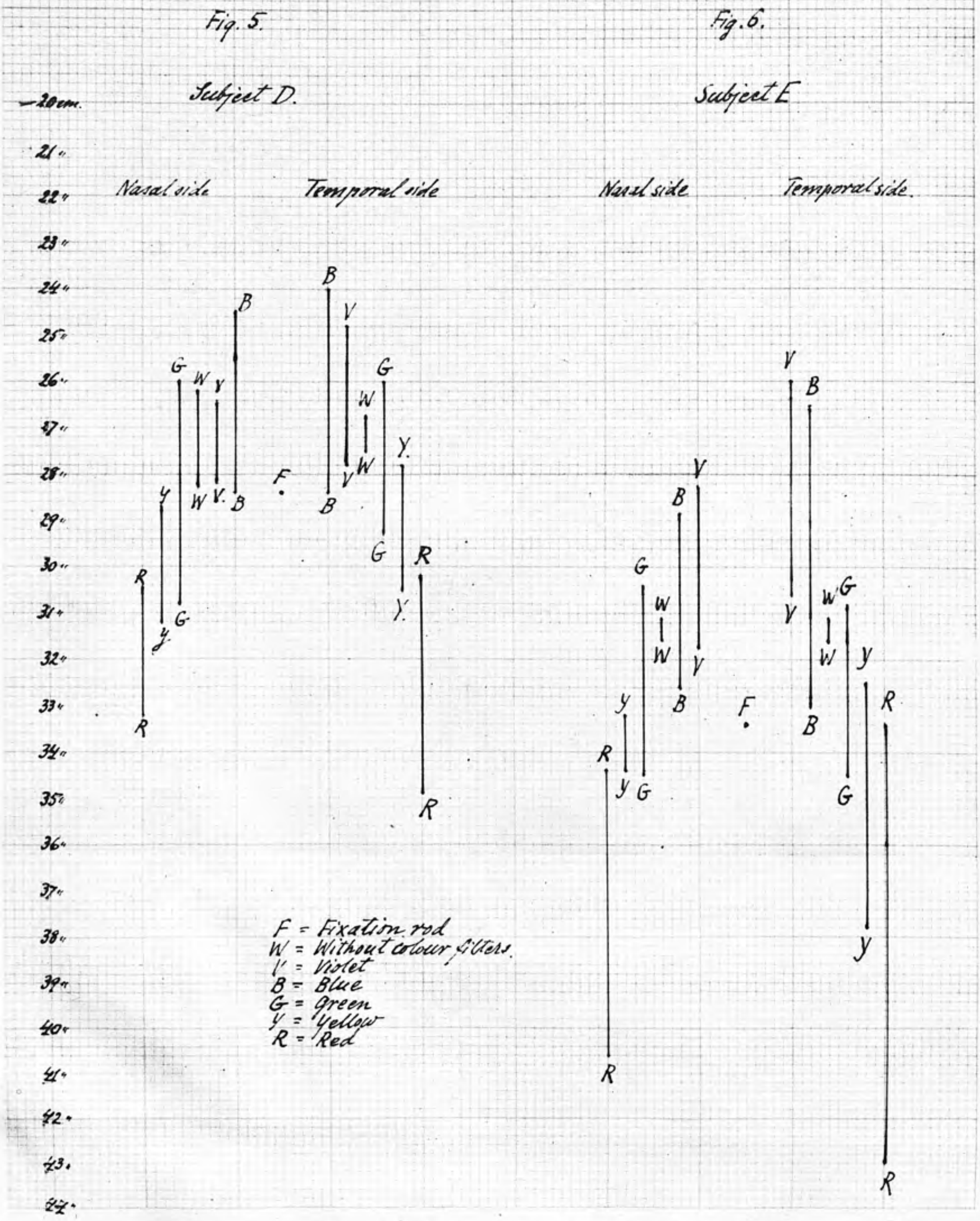
The results may be summarised as follows : In general the position of the near point of accommodation was found to be the nearest to the eyes for a violet filter and furthest away for the red filter. The sequence of the distances of the near point of accommodation for different colours was found to be as follows : violet, blue, green, yellow, and red.

Some discrepancies from these general results occured for the blue and violet colours, where the sequence was reversed as shown in fig. 3, but these might be ascribed to the fact that the difference in the wavelength of light passed through the mercury violet and the tricolour blue filters is small. /see table I/.

In case of young persons with normal eyes the differences between the two eyes were in general not significant as can be seen from fig. 3, but for older people like the author these differences may be considerable. In this last case the far point of

accommodation

The equidistant positions of the laterally placed rod
viewed through colour filters (Regions of)
Right eye



of accommodation could be determined as well as the range of accommodation. This was found different for the two eyes and also for different colours as shown in fig.4.

The results of the investigations on monocular vision are shown in figs. 5 and 6. In this case also two persons were tested more thoroughly and about four to seven series of observations were made for each colour and on each of the fixation rod. Figs.5 and 6 indicated that the regions of equidistance with the fixation point from the eyes are grouped in the same sequence as the near points of accommodation mentioned above i.e. the equidistant region for the violet colour is placed nearest to the eye, and colours again fall in the following order : violet, blue, green, yellow, and red. They frequently overlap especially the neighbouring ones, but it was always a striking experience that if the lateral rod was placed in the equidistant position for one colour and then the filter was replaced by another colour then generally a change in the distance of the lateral rod was observed : if the light passed through the filter was thus changed to a shorter wavelength the lateral rod was seen further away, and if the wavelength became greater the opposite was observed.

The results obtained here differ from those of Dr. Boniecka's experiments which were carried out with a different arrangement, but they are in agreement with

TABLE II.

Binocular vision. Depth perception of double images.

Colour filter on one, "Q" filter on the other eye.

Colour.	Image through colour filter seen			Total no. of obs.
	Nearer	Equidistant	Further	
Red	29	4	2	35
Yellow	20	11	3	34
Green	9	11	15	35
Blue	1	1	33	35
Violet	0	0	30	30

The figures represent the numbers of observations.

with the Matthissen formula mentioned above.

We summarise the results obtained in this series of experiments as follows : If we fixate monocularly one rod through a "Q" filter, and view a laterally placed rod through a colour filter, and try to establish the position of equidistance by moving the lateral rod only, then we find that the greater the refraction in the eye /the shorter the wavelength/ of light passing through the colour filter the smaller will be the geometrical distance of the la teral rod from the eye.

The establishment of the degree of this correlation requires a more detailed investigation.

The results of the investigation on double images are shown in tables II - VII. Table II indicates that in the case of binocular vision the image viewed through a red filter is seen nearer than the other image viewed through a "Q" filter, that on the contrary the image vewed through the blue and violet filters are seen further than those viewed through the "Q" filter. The yellow filter gives equal number of cases when the image is seen equidistant and nearer than the image through the "Q" filter, and with the green filter a larger number of cases with the images seen further away occurs. Here also the results indicate that the red image is seen nearest and the blue and violet furthest away which is equivalent to the results obtained with monocular vision where the regions of equidistance were in the inverted sequence. The fact is perhaps more strikingly illustrated

TABLE III.

Binocular vision. Depth perception of the double images.
Colour filters on both eyes.

No. of Combination	Colour on left eye	Colour on right eye	Left image seen.		
			Nearer	Equidistant	Further
1	Red	Yellow	9	9	3
2	"	Green	14	5	2
3	"	Blue	17	1	3
4	"	Violet	21	0	0
5	Yellow	Green	12	5	4
6	"	Blue	21	0	0
7	"	Violet	20	0	1
8	Green	Blue	14	4	3
9	"	Violet	21	0	0
10	Blue	Violet	9	5	7

No. of Combination	Colour on right eye	Colour on left eye.	Right image seen		
			Nearer	Equidistant	Further
1	Red	Yellow	9	9	3
2	"	Green	13	5	3
3	"	Blue	20	0	1
4	"	Violet	20	1	0
5	Yellow	Green	12	4	5
6	"	Blue	18	1	2
7	"	Violet	17	1	1
8	Green	Blue	15	5	1
9	"	Violet	15	2	2
10	Blue	Violet	16	6	3

TABLE IV.

Average normalised results for different combinations grouped together, from table III.

No. of Combinations grouped together.	Left Image Seen [1]			Right Image Seen. [2]		
	Nearer	Equi-distan	Further	Nearer.	Equi-distant.	Further
1/ 1+5+8+10	11	6	4	12	6	3
2/ 2+6+9	$18\frac{2}{3}$	$1\frac{2}{3}$	$\frac{2}{3}$	15	$3\frac{2}{3}$	$2\frac{2}{3}$
3/ 3+7	$18\frac{1}{2}$	$\frac{1}{2}$	2	$18\frac{1}{2}$	1	1
4/ 4	21	0	0	20	1	0

Remarks.

1/ Combinations of two neighbouring colours.

2/ Combinations with difference of two colours.

3/ Combinations with difference of three colours.

4/ Combinations with difference of four colours.

TABLE V.

Means of coloumns 1 and 2 of table IV.

No. of Combinations grouped together.	Image Seen		
	Nearer.	Equidistant.	Further.
1+5+8+10	$11\frac{1}{2}$	6	$3\frac{1}{2}$
2+6+9	17	$2\frac{2}{3}$	$1\frac{1}{3}$
3+7	$18\frac{1}{2}$	1	$1\frac{1}{2}$
4	$20\frac{1}{2}$	$\frac{1}{2}$	0

illustrated by the results of the second series of experiments shown in table III where different colours were put in front of each eye. The greater the difference in the wavelength the more striking are the differences in the depth perception. /tables IV and V/.

All the results quoted above were obtained with fixation of the nearer rod. When asked to fixate the rod situated further away the persons under test stated frequently that this was very difficult, if not impossible, and that the rod to be fixated was seen rather as two images inclined to each other at a small angle and also that these images could not be described as seen at the same distance from the eyes. This phenomenon was probably due to the fact that with different colours one cannot fixate properly an object, i.e. to accommodate both eyes on it by a simple convergence, but one sees it in double images in the same way as when a prism or a lens is placed in front of one eye. This phenomenon, however, requires a more detailed investigation and analysis. If we fixate a nearer object with different colours in front of each eye the incongruities mentioned above are of a much smaller degree, and in this case we may speak of a binocular fixation.

Besides the differences in depth perception between the two images by using different colours we observe several other phenomena.

When different colour filters are palced in front

front of both eyes various phenomena occured which were the subjects of investigations by many authors, Hering 24/ among the first of them. When different combinations of colours are used various processes like colour mixture, colour rivalry, etc. may take place. But in every case there exists one binocular field of vision in which the colouring and the outlines of objects may change, disappear and alternate, and two monocular fields of vision which are in general quite different from the binocular one and which are coloured with the colour placed in front of the corresponding eye. In the binocular field of vision we see a fixation rod and the double images of the further or nearer rod. The fixation rod is more stable than the double images which undergo various changes like inversions, disappearances, etc.; these changes are different for different duration of the fixation, for different combinations of colours and for differences between the two eyes. With different colours apart from the variations in the depth perception we observe also differences in the distinctness of the images, in size or thickness of the rods, and in the lateral distance of the double images from the fixation rod. All these changes are interesting because they all are related to the changes of the accommodation. All of them require special investigations. Our observations were mainly concerned with the changes in distinctness, and it was found that in 206 cases out of 282 the images seen less distinct

distinct were also seen further away. In 45 cases the difference in distincness was not accompanied by the perception of difference in the third dimension or vice versa. And in 31 cases the less distinct images were seen nearer. Thus it may be assumed that a relation also exists between the distinctness of the image and its depth perception. It was also observed that the most distinct are the images seen through the red filter and the least distinct through the violet filter, and the sequence of colours in this respect is again : red, yellow, green, blue, and violet, similar to that for the depth perception.

A sufficient number of observations concerning the size /thickness/ of the images could not be made and consequently the relation to the depth perception could not be obtained. The same applies to the observation of the lateral distances of the images from the fixation rod.

Neither the relation between the brightness and the perceived distance of the double images could be established. The experimental procedure did not allow us to estimate the difference in brightness of the images seen through the colour filters. The binocular field of vision in which the double images appear does not present any steady differences in brightness. It is rather uniform in this respect, although changing. Consequently in our experimental arrangement we could not draw any conclusions about the influence of of brightness on the depth perception of the double images. I want to stress however, that when the so called luminosity curve of the spectrum 10/, 16/ is taken into the account one should expect that the yellow green colours should appear nearer than the red and blue if the brightness should determine the perception of depth; and red and blue should give apprximately the perception of the same distance. Nothing of this kind was observed although we have seen that the difference in the depth perception between the green and blue or violet was much greater and more definite than between red and green. This might give rise to the supposition that the brightness may play some part in the depth perception in indirect vision.

Another interesting observation was also made. The two images were not seen parallell to each other but inclined at a certain angle. In the case of the combination of the "Q" and coloured filters this angle was greater for shorter wavelengths of light passed through the colour filter. The two images intersected above the visual plane when the nearer rod was fixated, and below the visual plane when the further rod was fixated. These phenomena also require special investigations.

All the results described seem to indicate that a definite relation exists between the wavelength of light used and the depth perception of the images in indirect vision.

Similar suppositions concerning the direct vision

TABLE VI.

Obsevations by Mr.Mc.D. corresponding to table II.

Colour.	Colour filter in front of the left eye. Left Image Seen		
	Nearer.	Equidistant.	Further.
Red	3	0	0
Yellow	3	0	0
Green	1	1	1
Blue	0	0	3
Violet	0	0	3
Total no. of obs.	7	1	7

Colour	Colour filter in front of the right eye. Right Image Seen		
	Nearer	Equidistant	Further
Red	0	1	2
Yellow	1	1	1
Green	1	0	2
Blue	0	0	3
Violet	0	0	3
Total no. of obs.	2	2	11

TABLE VII.

Observations by Mr. Mc.D. corresponding to table III.

No. of Combination	Colour on left eye.	Colour on right eye.	Left Image Seen		
			Nearer.	Equidistant.	Further
1	Red	Yellow	2	1	0
2	"	Green	3	0	0
3	"	Blue	3	0	0
4	"	Violet	3	0	0
5	Yellow	Green	3	0	0
6	"	Blue	3	0	0
7	"	Violet	3	0	0
8	Green	Blue	3	0	0
9	"	Violet	3	0	0
10	Blue	Violet	3	0	0
Total no. of obs.			29	1	0

No. of Combination	Colour on left eye	Colour on right eye.	Right Image Seen		
			Nearer.	Equidistant.	Further
1	Yellow	Red	0	1	2
2	Green	"	0	1	2
3	Blue	"	3	0	0
4	Violet	"	3	0	0
5	Green	Yellow	0	0	3
6	Blue	"	3	0	0
7	Violet	"	3	0	0
8	Blue	Green	2	1	0
9	Violet	"	3	0	0
10	Violet	Blue	0	1	2
Total no. of obs.			17	4	9

vision were made by several authors working on this subject /see Dawson[10], Hartridge[16] ,/, although some of them /Einthoven[12] and Bourdon[6] / attributed the differences in estimates of distance for different colours to the changes, and especially to the excentricy, of the pupil /pupils/.

Some differences in the depth perception due to the differences between the two eyes were also observed. For instance, during the preliminary adjustments for experiments Mr.Mc.D. always saw the right of the double images further away than the left, although he saw them laterally equidistant from the nearer fixation rod. Consequently when any colour filter was placed in front of his right eye he always saw the right image further away than the left image seen through the "o" filter. On the other hand, with the colour filters placed in front his left eye he saw red, yellow, and green images nearer abd blue and violet further away. This fact is indicated in table VI and also in table VII where differences in depth perception with different colours on each eye are shown.

These observations may help to devise some methods of measuring various characteristics of the eyes.

3

So far the investigations gave the following general results :

a/ Objects viewed in indirect vision through different colour filters are seen at different distances from the eyes.

b/ This phenomenon was observed both in the case of monocular vision, and also with double images in binocular vision.

c/ A relation seems to exist between the depth perception and wavelenth of light. Objects are nearer with longer wavelegths and further away with shorter wavelengths of light.

C

C. Depth perception in stereoscopic vision.

1.

The phenomenon of "walls".

In these investigations the depth perception of stereoscopic images of two objects were studied, while a third object situated betweem them was fixated. This case is of some interest because of certain positions of the fixation point some rather striking differences between monocular and binocular vision can be observed.

a.

The investigations were conducted as follows : Three rods were placed in the median plane : the nearest was placed at 34.6 cm., the furthest at 60.3 cm. from

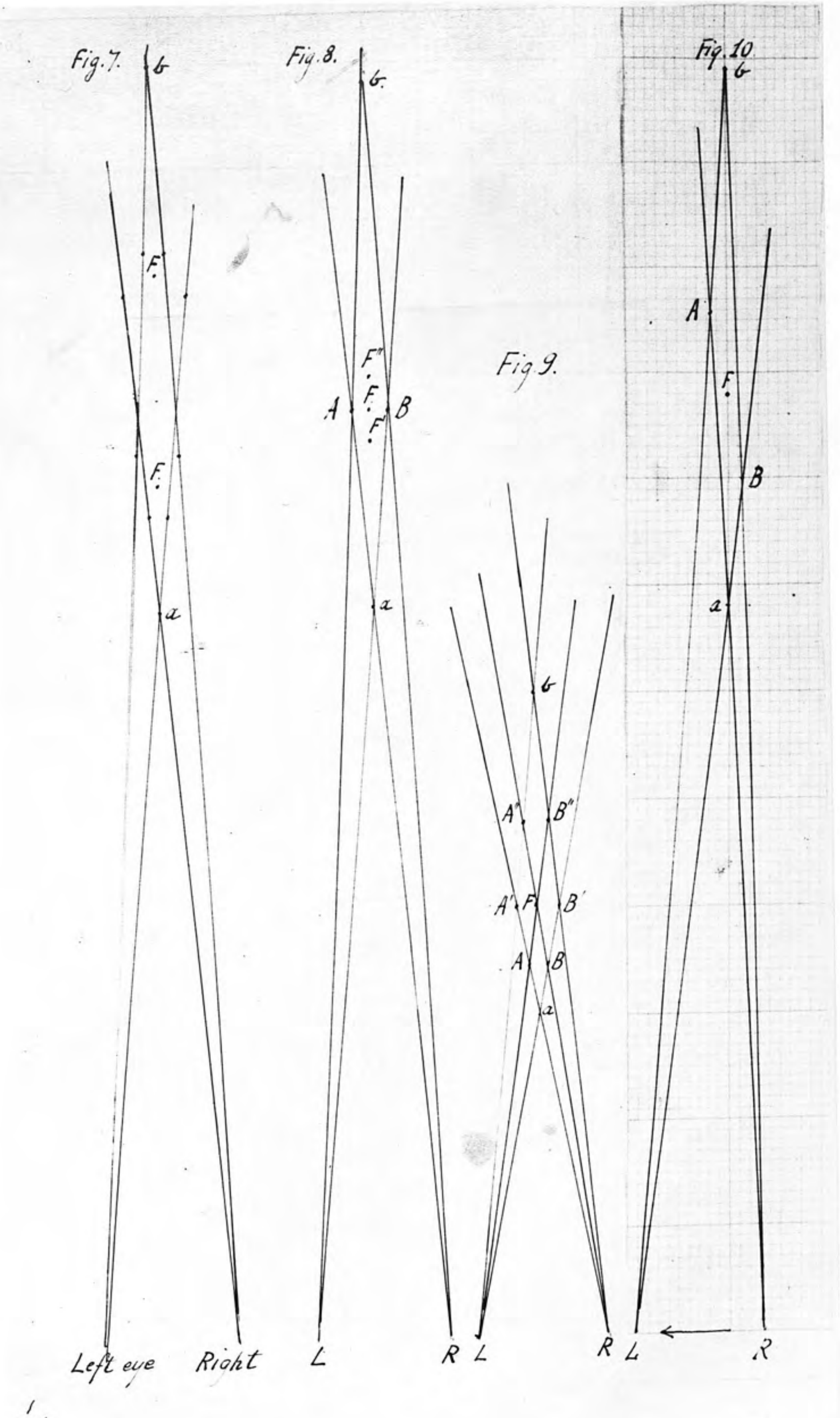


Fig. 7.
b
F.
F.
a
Left eye
Right
Fig. 8.
b.
F''
F.
F'
A
B
a
L
R
Fig. 9.
b
A'' B''
A' F B'
A B
a
L
R
Fig. 10
b
A
F.
B
a
L
R

from the eyes. These two rods were kept in their fixed positions, while the middle one which served as the fixation object was placed at different points in the median plane during the course of experiments. Thus in general two images of the nearer rod, and two images of the further rod could be seen. The double images of the nearer rod were crossed images, and of the further rod were uncrossed. The greater the geometrical distance of the fixation rod from the rod seen in double images the greater also was the lateral distance of both images from the fixation rod and from one another. Consequently when the distance from the fixation rod to the nearer rod was made much smaller than the corresponding distance from the further rod the double images of the nearer rod were seen closer together than the double images of the other rod. In this case four images were seen ; two inside ones of the nearer rod, and two outside images of the further rod. If on the contrary we place the fixation rod much nearer to the further rod we observe the opposite. Fig.7 illustrates those phenomena. There is a position of the fixation rod for which the double images of both rods are seen laterally equidistant from the fixation rod. In this case the crossed image of the nearer rod by the right eye covers the uncrossed image of the further rod by the left eye. In this case we can only see two images instead of four /apart from the fixation rod/.

This phenomenon however, is actually more complicated

complicated. Before we reach the described position we have a region where the double images of the nearer rod are yet seen nearer to the fixation point than the double images of the further rod but the difference is not sufficient to distinguish four images. They overlap. We see something like two walls inclined to each other, inside parts of which are formed by double images of the nearer rod and the outside parts by the double images of the nearer rod together with overlapping images of the further rod. If we move the fixation rod towards the further rod we have a region in which the opposite occurs i.e. the double images of the nearer rod are more distant laterally from the fixation rod than those of the further rod, although they are seen as two walls instead of four separate images.

The experiments were conducted in order to investigate the depth perceptions occuring when the fixation rod was moved about in the above mentioned regions.

Five persons were examined and the following results were obtained, When the fixation rod was placed at a distance of 42.5 to 43.1 cm. from the eyes /F' in fig.8/ the persons under test have seen two walls /A and B/ further away from the eye than the fixation rod. The inside parts of these walls were formed by the crossed images of the nearer rod and the outside parts by the images of the nearer rod together with the overlapping uncrossed images of the further rod formed behind the images of the nearer rod.; that could

TABLE VIII.

The "walls" phenomena.

Subject.	Distance of the fixation rod from the eyes when the "walls" are seen:		
	Further	Equidistant	Nearer
A	42,6 cm.	44,2 cm.	45,1 cm.
B	42,9 "	44,2 "	45,0 "
C	42,9 "	43,9 "	44,7 "
D	42,8 "	44,0 "	45,1 "
E	43,1 "	44,0 "	44,9 "

relatively to the fixation rod.

could be ascertained by closing the eyes alternatively.

When the fixation rod was placed at a distance of 43.9 to 44.2 cm. from the eyes /F in fig.8/ then the persons under test observed that the two walls were seen at the same distance as the fixation point or rather the nearer parts of the walls were seen nearer and farther parts further than the fixation rod. In this case the double images of the nearer rod covered the double images of the farther rod which were formed about the middle of the images of the nearer rod and behind them.

When the fixation rod was placed at a distance of 44.7 to 45.1 cm. from the eyes / F" in fig.8/ the both walls were seen nearer than the fixation rod. In this case the outside parts of the walls were formed by the crossed images of nearer rod while the inside parts by the images of the nearer rod together with the overlapping uncrossed images of the further rod, which were formed behind the images of the nearer rod.

Table VIII represents the means of three to five observations made by the five persons under test.

b.

To compare the binocular perceptions of depth the subjects were asked to close one eye first and then the other and to make the corresponding observations of the distance in the third dimension of the images of the rods seen laterally in comparison with the fixation rod. In all the positions of the fixation rod described above the nearer rod was seen nearer and the further one

one further than the fixation rod although the difference seemed to be much smaller than the actual geometrical distance. This fact is illustrated by the distance of double images shown in fig.7 ; it must be however understood that the positions of the images indicated in the figures have only a qualitative meaning since the actual positions of the images cannot be determined. In the cases where in the binocular vision the four double images are seen no essential difference occurs between the depth perception with the binocular and monocular vision, but only if a short time is allowed for the fixation. Some difference was observed when the fixation was prolonged. In that case by binocular vision one observed an inversion in which the double images of the further rod were seen nearer than the fixation point. This kind of inversion occurs also in monocular vision but it comes after a much longer fixation and it is not so persistent as in the case of double images.

In the cases when one cannot distinguish the four images by binocular vision /two"walls" seen/ as illustrated by fig.8, no difference between the binocular and the monocular depth perception can be observed only for the central position of the fixation point /F in fig.8/. In the case when the fixation point is in F′ at which by binocular vision the two walls are seen further away than the fixation rod, in monocular vision the images of the nearer rod are seen nearer, and in the case of fixation point at F" in which by binocular

binocular vision the two walls are seen nearer than the fixation rod, in monocular vision the two images of the further rod are seen further away.

The case illustrated in fig.8 with fixation point at F i.e. when no difference (in distance) between the walls and the fixation rod is observed and all the three rods are placed in the median plane the following observations were also made. When the nearer rod was fixated four double images equally spaced laterally were seen : two inside ones of the middle rod and two outside of the further rod, and the lateral spacing of all the images was equal. A similar phenomenon occured when the further rod was fixated. This observation is illustrated by fig.9 from which we may conclude that in this case the double images are seen at A, B, A′, and B′ when the nearer rod is fixated, and at A′, B′, A″, and B″ when the further rod was fixated, because otherwise no equal lateral distances could be obtained. This observation may lead to a new approach to the location of the double images in third dimension.

c.

Apart from this the following other observations were made :

1/ When in the position illustrated by the fig.8 with fixation point at F we move the head laterally we can observe that the wall on the opposite side to the direction in which the head is moving approaches the observer and the other wall moves away from the observer,

Fig 11.

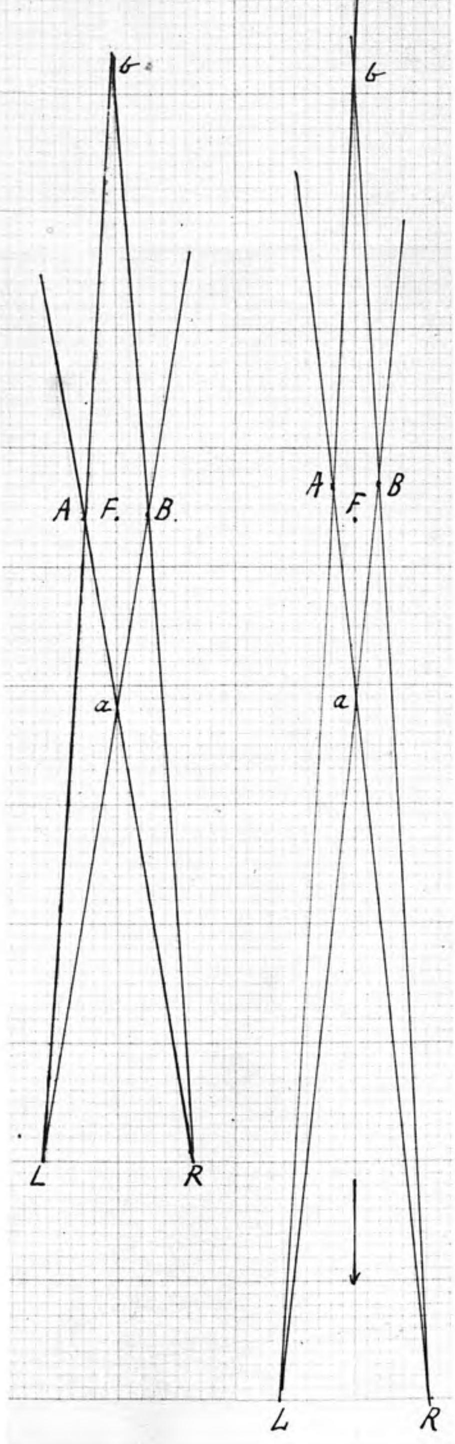


Fig. 12.

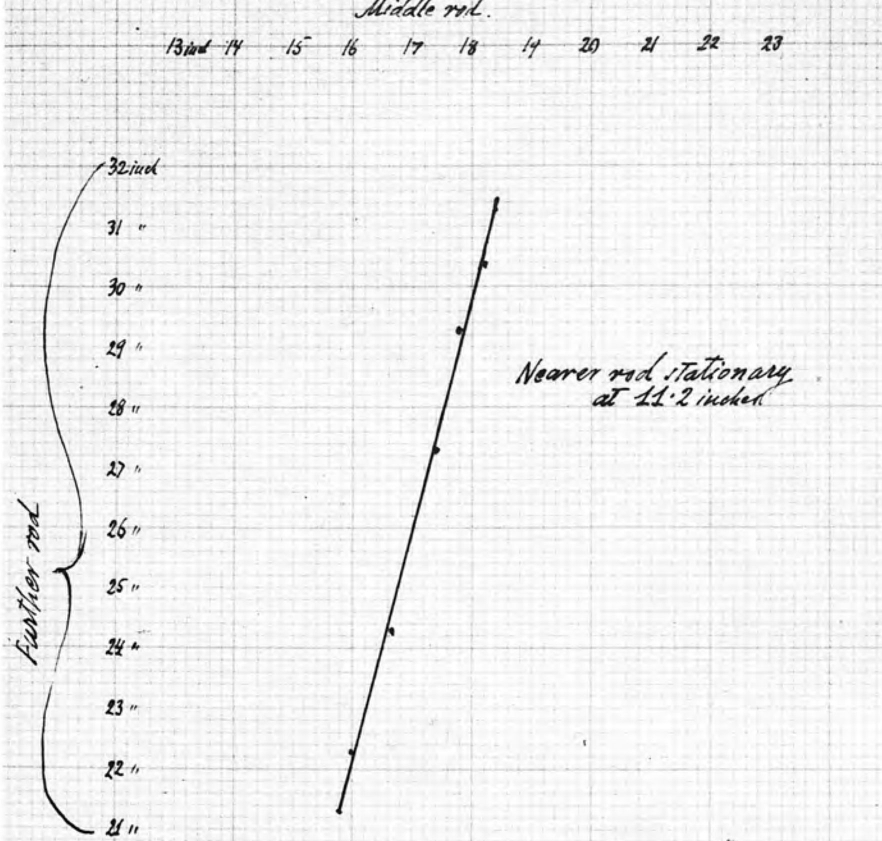
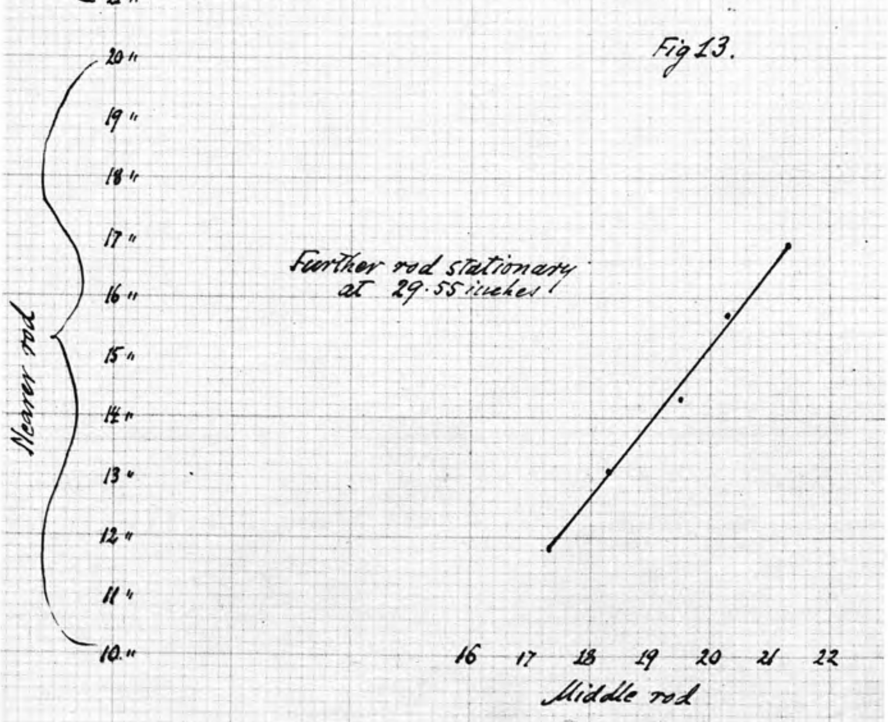


Fig 13.



observer, i.e. if we move the head to the left the right wall moves forward and is seen in front of the fixation rod, and the left wall moves away and is seen behind the fixation rod /fig.10/. This movement is continuous so the greater the displacement of the head the greater laso becomes the difference in the third dimension between the two walls.

This phenomenon is also observed in other positions of the fixation point /F′ and F″ in fig.8/ ; in these cases the difference occurs between the position of both walls although both may be seen behind or in front of the fixation rod.

If we now examine the composition of the walls during the movements of the observer's head we find that it is changing. In the walls moving towards the observer an image of the nearer rod forms the outside part and the two images of the nearer and further rod overlapping form the inside part, while in the wall moving away the opposite occurs.

2/ When in the position of fig.8 with fixation point at F and F′ the persons under test moved the head away from the screen thus increasing the distance of the fixation rod from the eyes the two walls were seen coming closer together and receding from the observer into the region behind the fixation point /fig.11/. When the observer moved his head in the opposite direction the opposite phenomenon was observed.

3/ When in the position indicated in fig.8 with

with fixation point at F different colour filters were placed in front of both eyes the differences in the third dimension of both walls were observed.

If a red filter was placed in front of the left eye and the blue filter in front of the right eye, the right wall was seen nearer and the left one further away than the fixation rod. When the colour filters were interchanged the opposite occured. This is in agreement with the results obtained in our previous experiments on the influence of colours on depth perception in the indirect vision. But here we were dealing with the crossed images of the nearer rods while previously we made experiments with the uncrossed images. The position of the walls and their composition is similar to that in the fig.10, When the red filter is placed in front of the left eye and blue in front of the right eye, and opposite, when the filters are interchanged. This suggests that the phenomena occuring here are similar to those obtained in the previous experiments which resulted in the observation of the shortening of the lateral distance from the fixation rod of the image seen through the filter of shorter wavelength. This effect was more pronounced for violet or blue colours than for yellow or red.

d.

Further investigations were conducted with the aim to establish the relation between the distances of the three rods from the eyes at the position at which

Fig. 14.

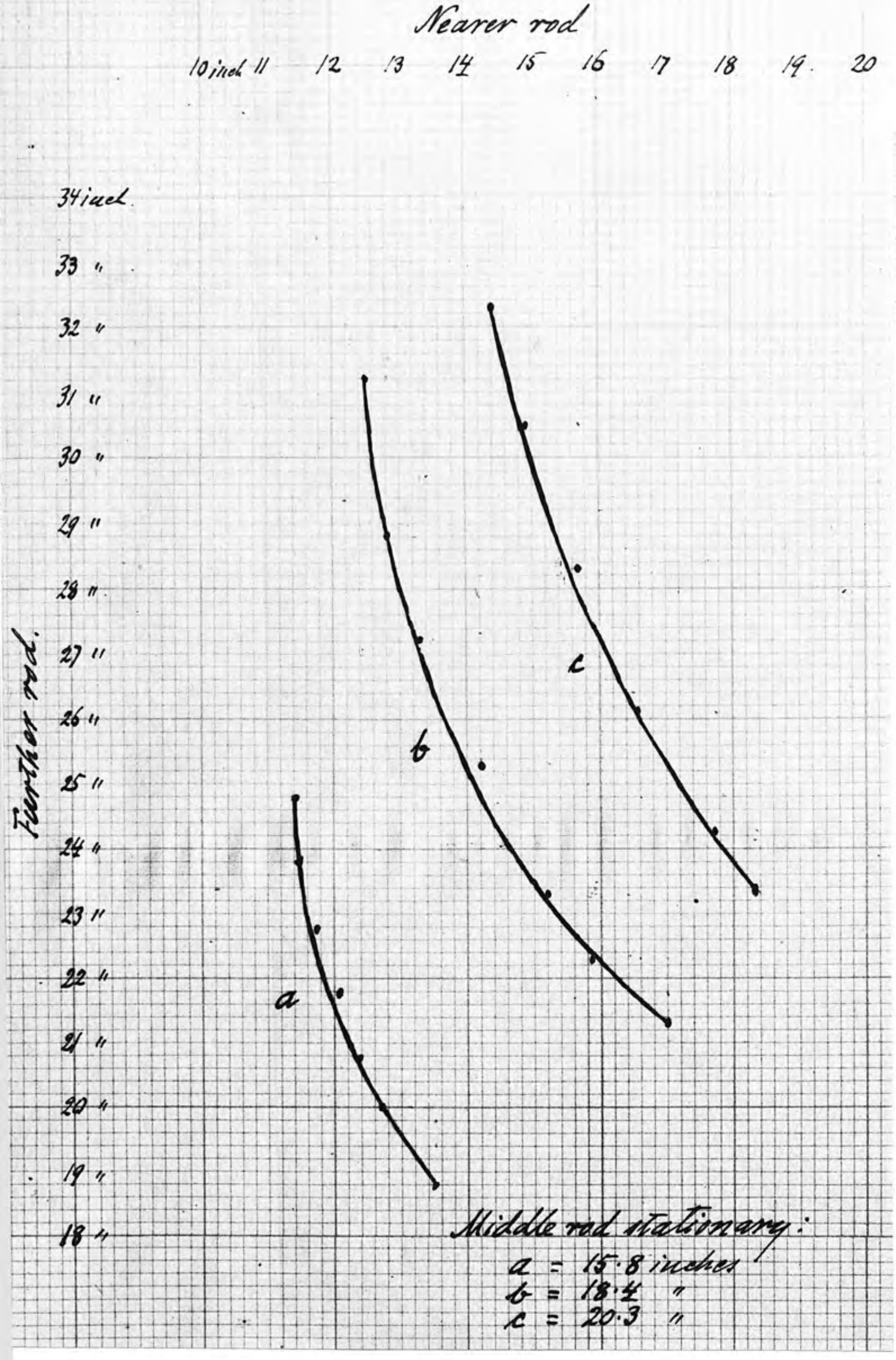


Fig. 15.
$\alpha_l = \beta_l = \alpha_r = \beta_r$
$\alpha_l + \beta_l = \alpha_r + \beta_r$
A, B same distance as F.

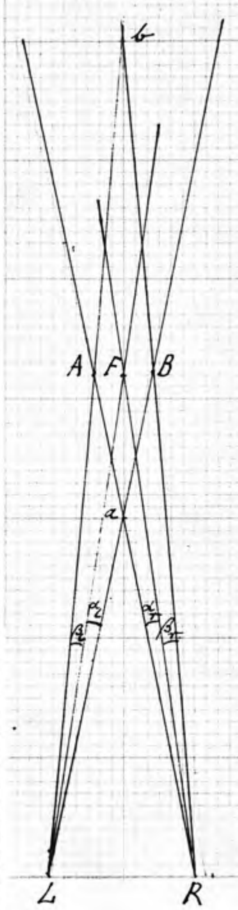
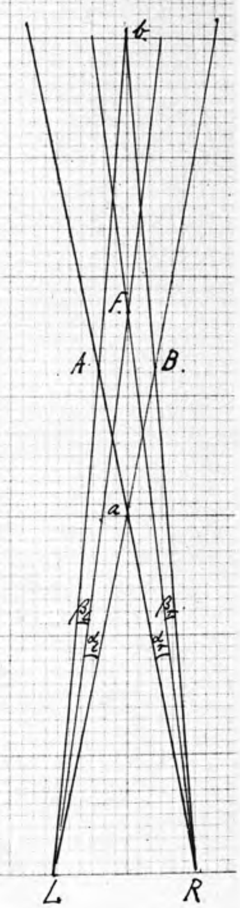


Fig. 16.
$\alpha_l > \beta_l, \alpha_r > \beta_r$
$\alpha_l = \alpha_r, \beta_l = \beta_r$
A, B nearer than F.



which the two walls were seen equidistant with the middle fixation rod. For this purpose we kept one rod stationary, altered the position of the second rod, and found the corresponding position of the third. When the nearest rod was kept fixed the fig.12 shows that the relation between the distances of the other two rods can be approximately represented by a straight line. The fig.13 shows the relation between the positions of the nearest and the middle rods, while the furthest rod was kept stationary. In this case also the relation is approximately linear although inclined at a different angle. When the middle rod is kept fixed the corresponding curves for the nearest and furthest rods are no longer straight lines, and are shown in fig.14. These three relations supplemented with further results may lead to the establishment of a formula.

Other observations were also made. We compared the lateral distances of the nearest and furthest rods from the middle one, when observed with one eye. From these observations a very simple formula seems to arise ; namely that in the position of the rods when the two walls are seen equidistant the angular distances of the two outside rods from the middle one are equal. If we call the angle subtended at the eye by the nearer and the middle rod α_l for the left eye and α_r for the right eye, and β_l and β_r the corresponding angles for the further rod, then in the case when the two walls are seen equidistant /fig.15/ $\alpha_l = \beta_l$ and $\alpha_r = \beta_r$

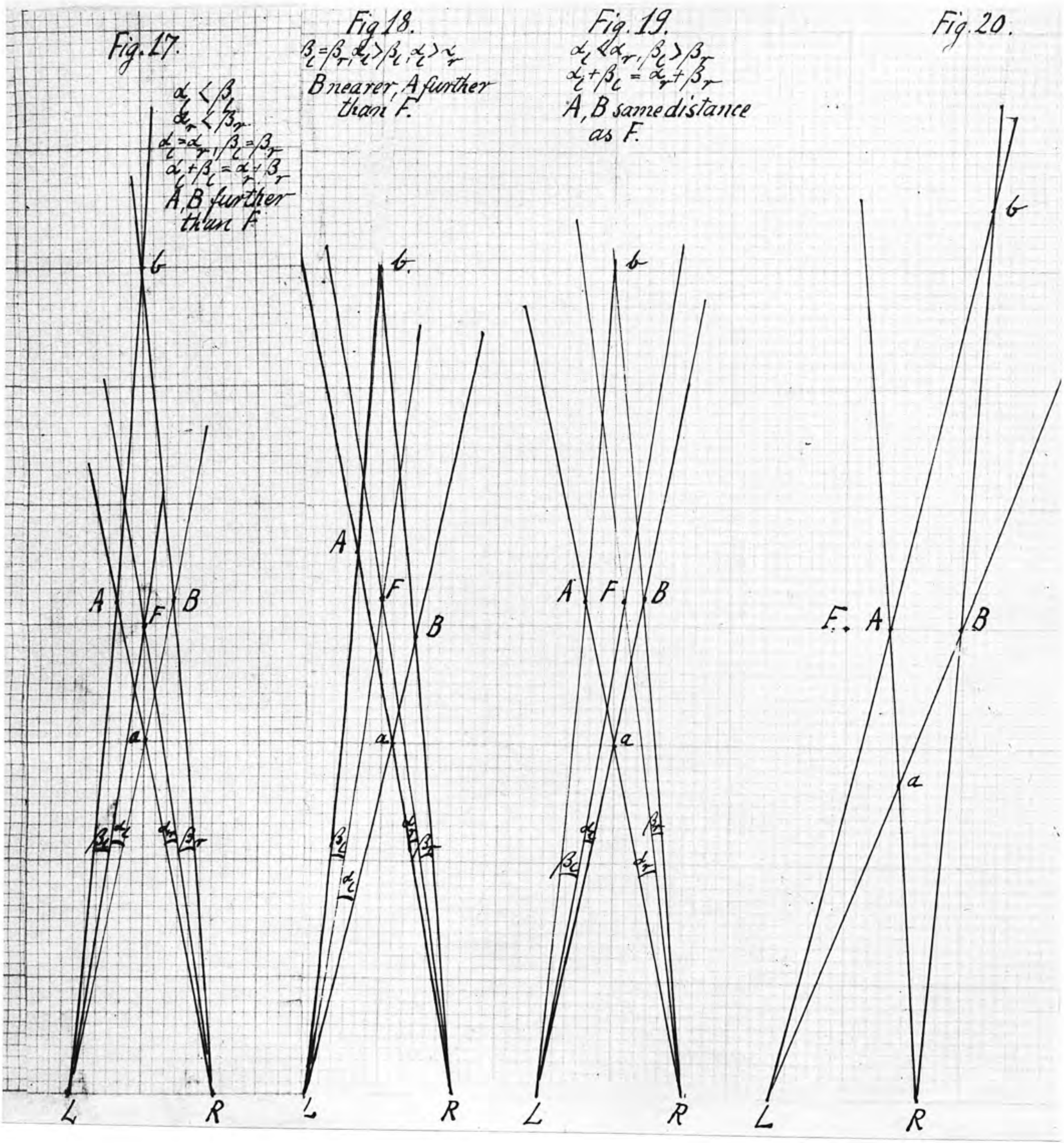


Fig. 17.
α_l < β_l
α_r < β_r
α_l = α_r, β_l = β_r
α_l + β_l = α_r + β_r
A, B further than F
b
A
F
B
a
β_l
α_l
α_r
β_r
L
R
Fig 18.
β_l = β_r, α_l > β_l, α_l > α_r
B nearer, A further than F.
b.
A
F
B
a
β_l
α_l
α_r
β_r
L
R
Fig. 19.
α_l < α_r, β_l > β_r
α_l + β_l = α_r + β_r
A, B same distance as F.
b
A
F
B
a
α_l
β_l
β_r
α_r
L
R
Fig. 20.
b
F. A
B
a
L
R

$\alpha_r = \beta_r$ and $\alpha_l = \alpha_r$ and $\beta_l = \beta_r$. When $\alpha_l > \beta_l$ and $\alpha_r > \beta_r$ and $\alpha_l = \alpha_r$ and $\beta_l = \beta_r$ /fig16/, then the walls are seen nearer than the fixation rod. And when these relations are reversed /fig.17/, the walls are seen further away.

We then investigated the effect of moving the middle /fixation/ rod, while the two outside ones were stationary. When the middle rod was moved towards the observer / always in the median plane/, the two walls were seen first further away than the fixation rod until a point was reached when the rods were seen in separate double images. A similar observation but in the reverse direction was made when the middle rod was moved away from the observer.

When the near rod was moved towards the eyes from the position when the walls were seen equidistant, we observed that the walls approached towards the eyes in comparison with the fixation rod, until the position was reached when we saw the double images separately. When the nearer rod was moved away from the eye the corresponding reverse phenomenon was observed.

When similar changes in the position of the furthest rod were made, similar phenomena were observed but less pronounced.

We also made some observations with lateral movements of the rods. If we start with the position of the rods shown in fig.15 i.e. the two equidistant walls are seen, and moved the nearer rod some 1 to 2 mm. to the right /fig.18/, we saw the right wall B coming

coming nearer and the left wall A receding behind the middle fixation rod. In this case the angles β_l and β_r remained equal and unchanged, but the angle α_l became greater than α_r and also greater than β_l and $\alpha_l+\beta_l > \alpha_r+\beta_r$. In this case the right wall is composed of the image of the nearer rod belonging to the left eye which forms the outer part of the wall and the image of the nearer rod with the overlapping image of the further rod belonging th the right eye form together the inner part of the wall. The left wall has the reverse composition. If we move the nearer rod to the left the phenomenon is reversed.

Corresponding phenomena were observed when lateral shifts were made of the further rod, the other two being kept stationary. For instance when the further rod was moved to the right the observations were similar to those made when the nearer rod was moved to the left, but less pronounced.

When lateral movements of the rods were continuous, continuous changes in depth were observed.

When the middle fixation rod was moved laterally no similar phenomenon occured. In this case no change of the distance of the walls from the eyes was observed /in comparison with the middle rod/. On the other hand the lateral distances of the two outside rods from the middle one were seen to change when viewed monocularly. If the middle rod was moved to the right a small distance of some 2 mm. /fig.19/, the angle α_l became

became smaller than β_l but α_r greater than β_r , but in this case $\alpha_l + \beta_l = \alpha_r + \beta_r$. This indicated that only differences between the total angular distances $\alpha_l + \beta_l$ and $\alpha_r + \beta_r$ are related to the differences in depth perception, which has been proved in further investigations.

The "walls" can be observed not only when the rods are placed in the median plane or not far from it, but also for other position of the rods as is shown in fig. 20 and the relations are similar to those in the previous cases.

There is one more striking phenomenon which could be expected from the above observations, and which was actually verified by observation. If the nearer rod, instead of being perfectly straight throughout its whole length, and placed vertically, has a curved region in the middle with convex side to the left, and the top straight part is inclined at a small angle to the right, then we expected that the two walls should assume the following shape : They should both be equidistant from the observer at the bottom. The right wall should be curved away from the observer in the middle and inclined towards the observer at the top. The curvatures of the left wall should be reversed. This was indeed observed, and thus was confirmed the rule that where the image of the further rod formed together with the image of the nearer rod the inner parts of the wall, there the wall had to be seen nearer than the fixation rod, and vice versa. This last observation was a case of a continuous

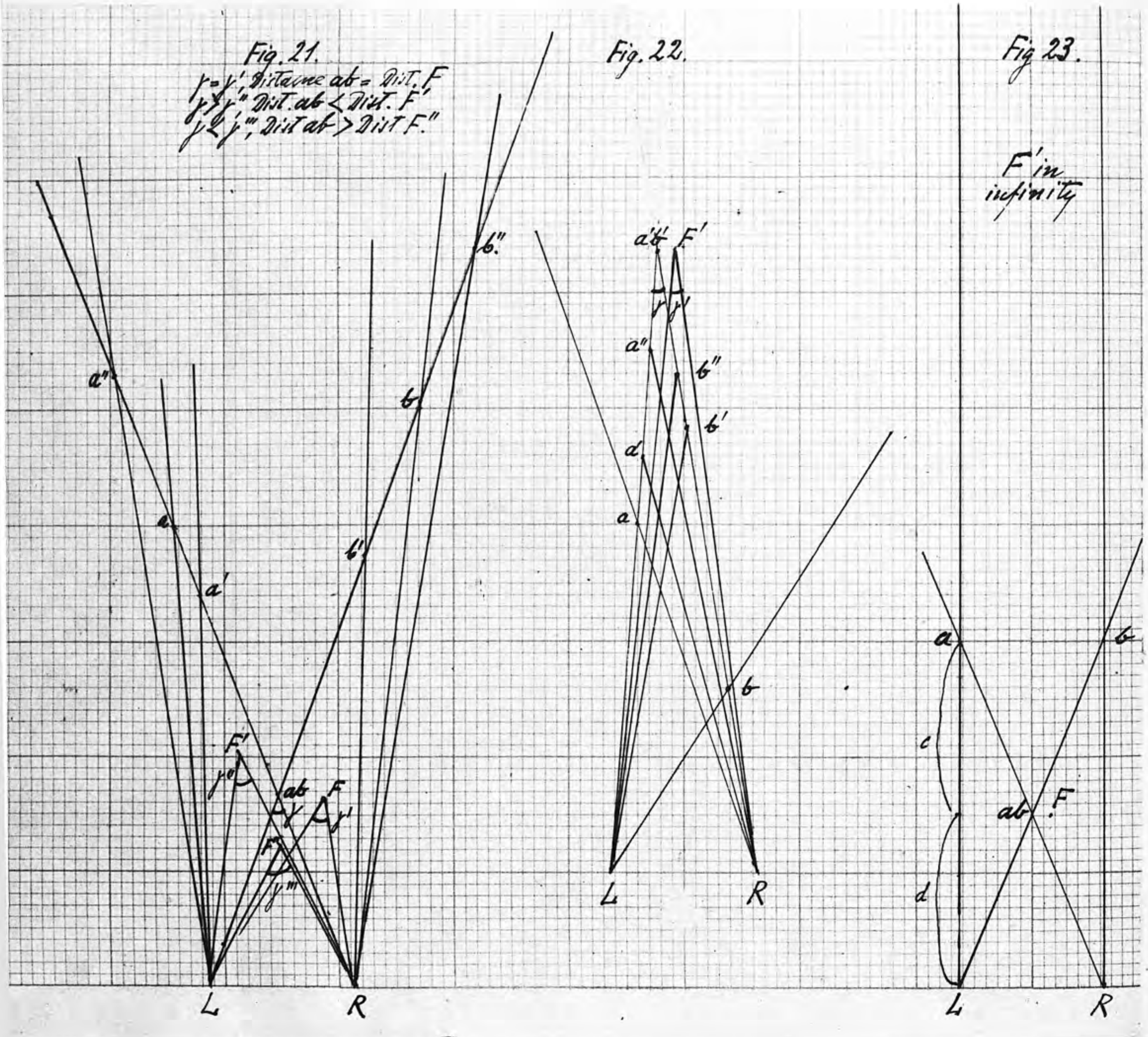


Fig. 21.
γ = γ', Distance ab = Dist. F
γ > γ'' Dist. ab < Dist. F'
γ < γ''', Dist ab > Dist F''
a''
a
a'
b''
b
b'
F'
ab
F
L
R
Fig. 22.
a'b' F'
a''
b''
b'
d
a
b
L
R
Fig 23.
F' in infinity
a
b
c
d
ab
F
L
R

continuous (change) in shape or distance, and it included most of the phenomena previously described. A similar effect occurs, when instead of a curved rod we place between the eye or eyes and a straight rod an unregularly curved lens /aniseiconic glasses/.

Most of the observations on the "wall" phenomena were made and confirmed by the five persons under test.

2.

Other stereoscopic phenomena.

a.

The phenomenon just described presents an until now unrecorded example of a stereoscopic vision in which two stereoscopic images are seen and no other images occur. These inspired the author to further investigations which would enable us to find a relation between these and other stereoscopic phenomena.

When there are two rods placed somewhere in front of the eyes we can chose a fixation point for which only one stereoscopic image is formed, and in addition two monocular images are seen. Fig. 21 illustrates this case, a and b represent the geometrical positions of the rods, and ab the stereoscopic image composed of the image of a by the right eye and of b by the left eye. The rod F placed at the same distance as ab serves as the fixation point. The condition for this to occur is that if F is fixated ab lies on the horopter, i.e. the

the angle subtended by the eyes at F is equal to the angle subtended by the eyes at ab. If the agle γ''' is slightly greater than γ we see the stereoscopic image further away than F", if slightly smaller the image ab is seen nearer than the fixation point. If the difference in the distance of ab and F is increased the stereoscopic image ceases to be seen and the four double images appear. In the case when one stereoscopic image is seen we see also two monocular uncrossed images which appear further away than the fixation point and the image ab.

A similar phenomenon occurs also when we place the fixation point behind the two rods a and b. In this case the image a'b' in fig.22 is the stereoscopic image of b seen by the right eye and the image of a seen by the left eye lying in the horopter with the fixation point F' and is seen at the same distance from the eyes as F' ; on the left is seen in this case a monocular image of a by the right eye, and on the right the monocular image of b by the left eye, both being crossed images, and are seen nearer than the fixation point and the stereoscopic image a'b'. If F' is placed slightly nearer than the image a'b' i.e. when the angle γ' is slightly greater than γ , we see again the image a'b' further away than the fixation point, if slightly further, a'b' is seen nearer than F'.

Figs.21 and 22 show that the geometrical distance of the rods a and b may be different and still the stereoscopic image ab or a'b' could be seen at the same

same distance as the respective fixation point provided that the rod a is placed in the same visual direction of the right eye and b of the left eye as in the case illustrated by fig.21, and vice versa in fig.22. In both cases only the shape and the size of the stereoscopic image change in accordance with the changes in the visual angles at which the rods are seen ; this problem of the changing shape and size will be discussed separately.

One can also observe the changes of the lateral distance and of the depth of the monocular images in comparison with the fixation rod and with the stereoscopic image.

In fig.23 the lateral distance between the rods a and b is the same as the distance between the centres of the eyes. In this case no stereoscopic image can be obtained if we try to find a fixation point beyond the rods because the visual axes are parallel i.e. intersect at infinity. We can also see that if we now increase the lateral distance between the rods we cannot obtain any stereoscopic image with the fixation point behind the rods, and only four double images can be seen. If a nearer fixation point is chosen its position must be half way between the rods and the eyes in order that a stereoscopic image should be obtained at the same distance. In this way we could measure the distance between the centres of the eyes.

The case in fig.22 represents the same phenomenon

The case in fig.22 represents the same phenomenon which we obtained in all kinds of stereoscopes . In the stereoscope there is no material fixation point and consequently the relative position of the stereoscopic image with respect to it cannot be determined, if no special arrangement is made. Also fewer monocular images are seen than in the described natural setting since the object presented to the left eye is not seen by the right eye and vice versa.

If we compare the figs. 21 and 22, we see that the stereoscopic images of the rods placed geometrically at the same distance appear in the case 21 much nearer than in the case 22 /equidistant with the fixation points, which are placed nearer in case 21, and further away in case 22/. The persons under test have confirmed this. This also seem to explain the phenomena described by H.Carr 8/ in which Miss Jessie B. Allen could at will see alternately the stereoscopic images nearer to the eyes, or much further away. She could, I suppose, change at will from the nearer fixation point /case 21/ to the further fixation point /case 22/. The author of this paper also possesses this ability.

The phenomenon illustrated by fig.21 can be also observed in a very natural setting. Suppose, we look at two similar nails placed on a wall in such a position that the line joining them is parallel to the line through the centres of the eyes. If now, we place a a finger in front of the eyes in such a position that the double images of the finger appear just below the two nails, i.e. have the same lateral distance between them, and then we pass to the fixation of the top of the finger, we seen one stereoscopic image of the nails just above the finger, and at the same distance, and two monocular images of the nails. In this case the angles subtended by the two eyes at the fixation point and at the stereoscopic image are equal. If we now move the finger slightly towards the eyes the stereoscopic image is seen behind the finger, and if the finger is moved slightly towards the wall the stereoscopic image of the nails is seen nearer than the finger, although this might appear very queer. In the first case the lateral distance between the double images of the finger, when a point on the wall is fixated is greater than that between the nails, and the angle at which these double images appear is greater than that of the two nails. The opposite can be observed in the second case.

b

An arrangement was chosen in further investigations which was similar to the Meyer's[32] experiments with wall paper designs. Three rods were situated in the same plane perpendicular to the plane containing the visual axes and placed at the same lateral distances from each other. It was found that when a fourth rod was placed at one particular distance and fixated the other three rods were seen in four images of which two inside ones

TABLE IX.

Stereoscopic phenomena with three rods and near fixation point.

Distance of the 3 rods from the eyes.	Lateral distance between the rods.	Distance of fixation rod from the eyes when seen equidistant with stereo--scopic images.
20 inches	2.0 inches	10.9 inches
20 "	1.8 "	12.8 "
20 "	1.6 "	12.2 "
20 "	1.5 "	12.25 "
20 "	1.25 "	13.0 "
16.8 "	2.0	9.5 "
16.8 "	1.62 "	10.25 "
16.8 "	1.25 "	11.3 "
16 "	2.0 "	8M92 "
14 "	2.0 "	7M82 "
14 "	1.5 "	8.85 "
12 "	2.0 "	6.75 "

If the distance of the rods from the eyes is kept constant while the lateral distance between the rods is decreased then the distance of the stereoscopic images from the eyes increases. If the lateral distance between the rods is kept constant and their distance from the eyes is decreased then the distance of the stereoscopic images also decreases.

Fig. 24.

$$\alpha_l + \beta_l = \alpha_r + \beta_r$$
$$\gamma = \gamma' = \gamma''$$

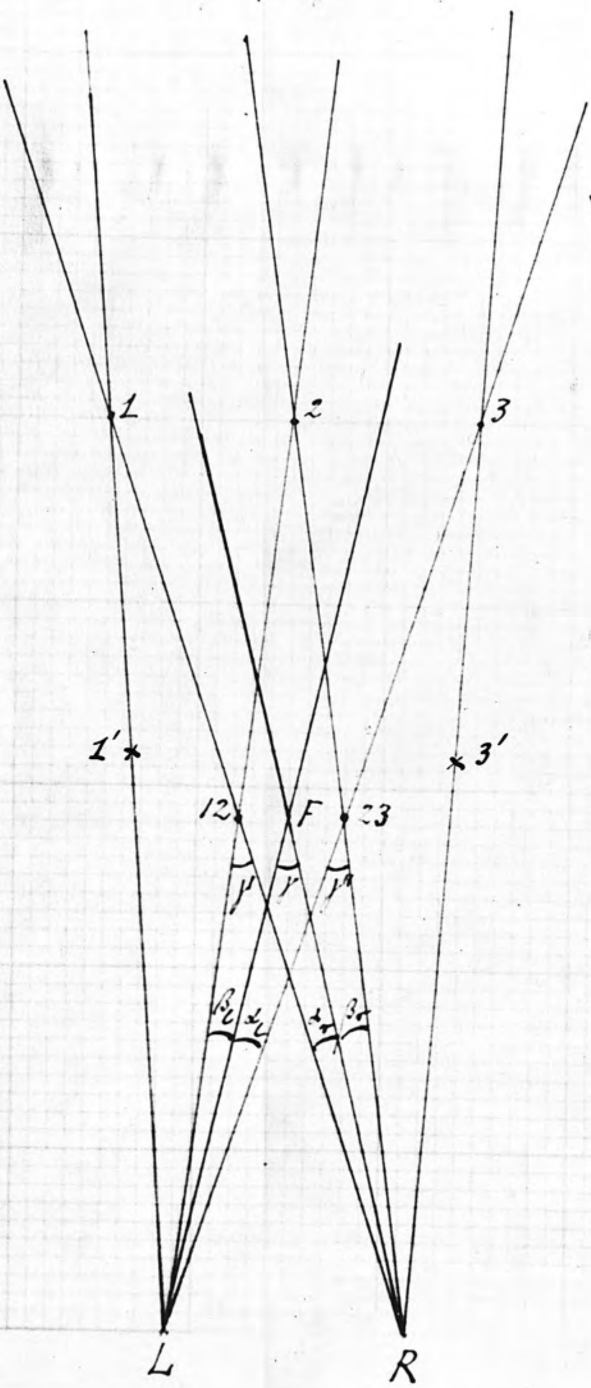
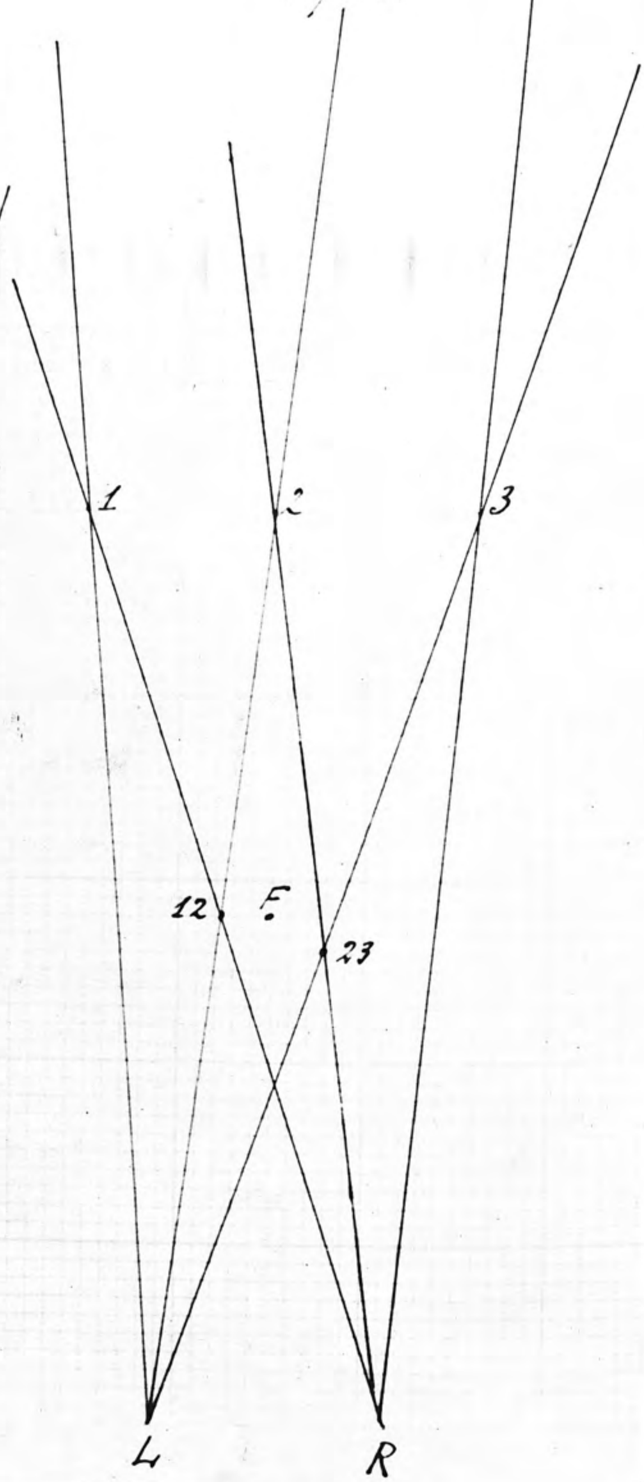


Fig. 26



ones were formed by the stereoscopic process from two neighbouring rods and the outside images were the monocularly seen outside rods. The inside images were seen at the same distance from the eyes as the fixation rod ; the equidistance of the stereoscopic images with the fixation rod was very definitely ascerted by the persons under test even if the fixation rod was not in the range of accommodation of the eyes. The relative distance of the outside rods in comparison with the two inside ones and with the fixation rod was not so certain and changed with the duration of the fixation ; generally they were seen further away than the fixation rod and the stereoscopic images ; the stereoscopic images remained very stable even if the fixation was much prolonged. Table IX gives some examples of relations between the geometrical distances of the rods from the eyes and from one another and the distance of the fixation rod, and the fig. 24 gives a geometrical construction where 1, 2, 3 represent the rods, F the fixation rod, 12 and 23 the stereoscopic images seen at the distance of F, and 1' and 3' the monocular images of rods 1 and 3. The figure shows how from this geometrical construction it is possible to determine the position of the fixation point when the position of the other three rods is chosen. We see also that this relation can be formulated in terms of angles: if we define the angles as shown in the fig. 24 the condition for this phenomenon is that $\alpha_l + \beta_l = \alpha_r + \beta_r$, and that the fixation point is so situated that the

Fig. 25.

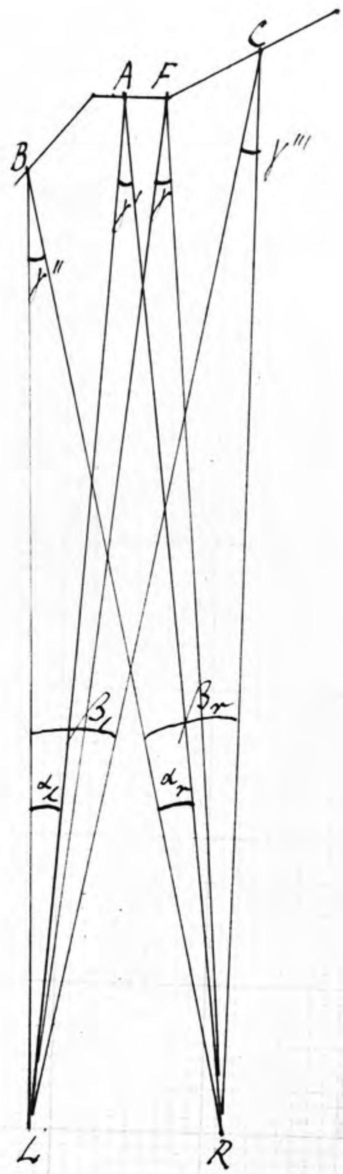
$\gamma = \gamma'$ A same distance as F.

$\gamma'' > \gamma$ B nearer than F.

$\gamma''' < \gamma$ C further than F

$\alpha_l > \alpha_r$ A further than B

$\beta_l < \beta_r$ B nearer than C



the angles γ , γ', and γ'' are equal, which occurs only when F lies in the plane of 12 and 23. If we move F from the plane towards the eyes or away from the eyes the stereoscopic images appear respectively further or nearer than the fixation point. It is understood that the movements of the fixation rod from the equidistance position can be only small because otherwise the stereoscopic images become double images.

Also other phenomena similar to those perceived in the first stereoscopic experiments can be observed. Thus if we increase the lateral distance of one of the rods the seen distance of the stereoscopic image on the same side becomes smaller and if the lateral distance is decreased the distance of the corresponding stereoscopic image grows. This can be seen from fig. 26. If the lateral movement of the rod is continuous we observe continuous changes in depth of the stereoscopic images.

If we now compare the relations between the angles subtended at the eyes and depth perceptions of stereoscopic images with the corresponding relations for objects seen singly in binocular vision and situated at the points of intersection of the visual lines, we can state that the relative position in the third dimension of these objects would be the same as that of the corresponding stereoscopic images /i.e. formed in the same places/. This is shown in fig. 25. This can lead us to the generalisation of the principles

Fig. 27.

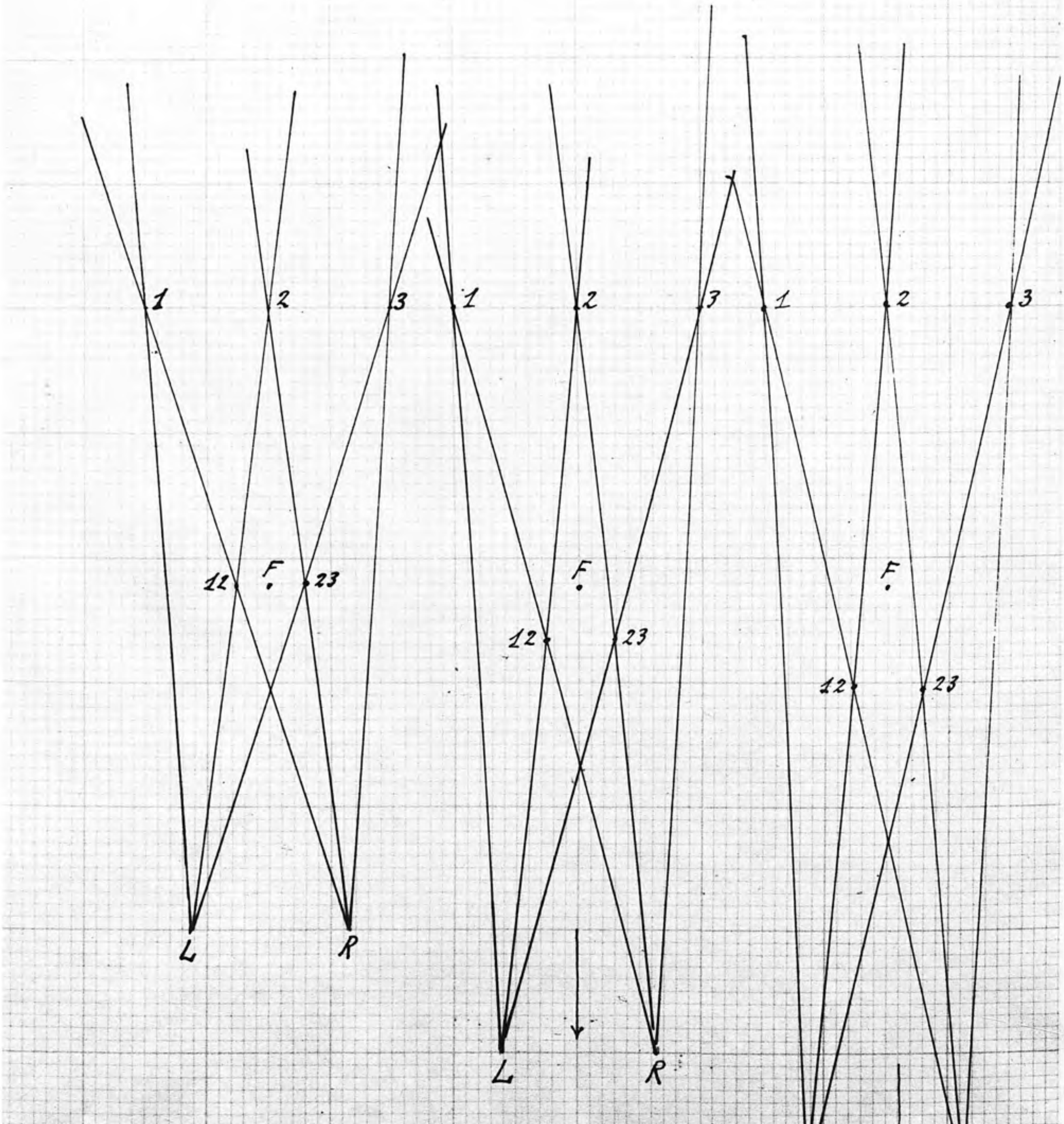


Fig 28.

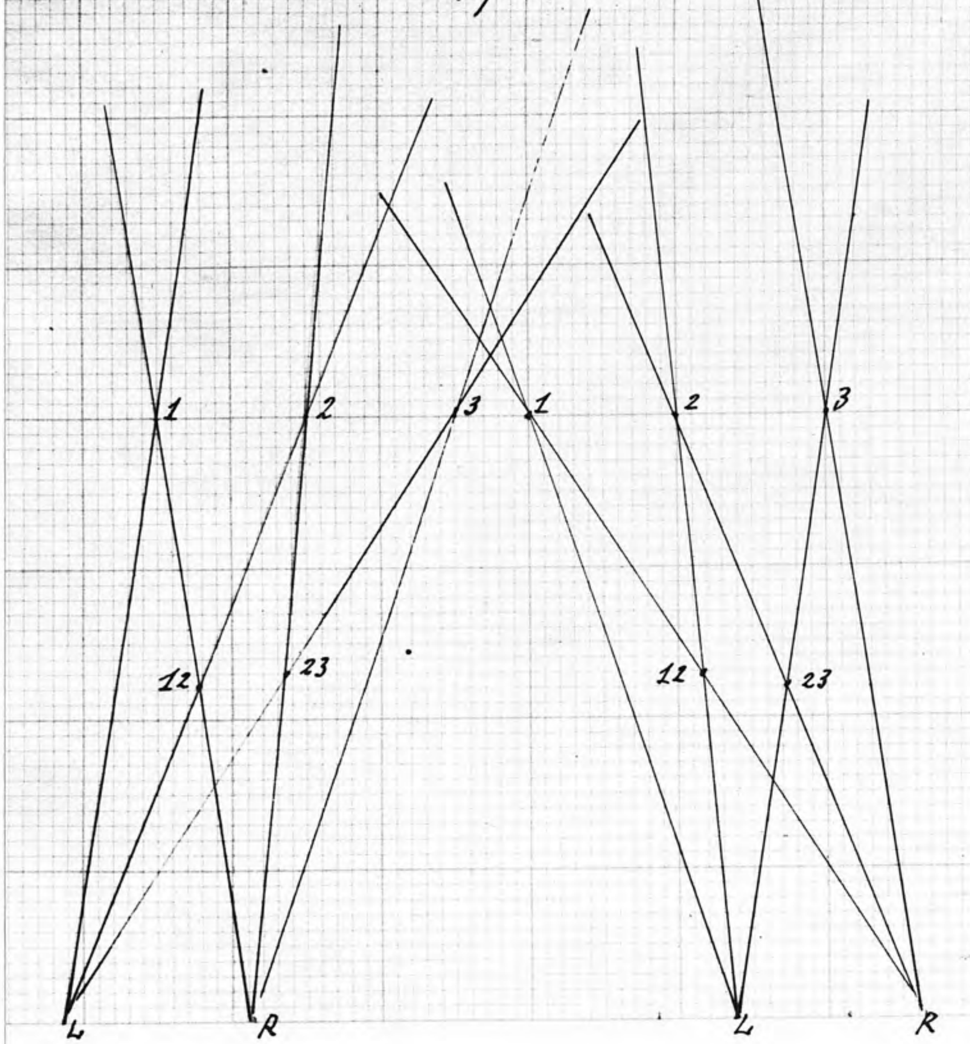
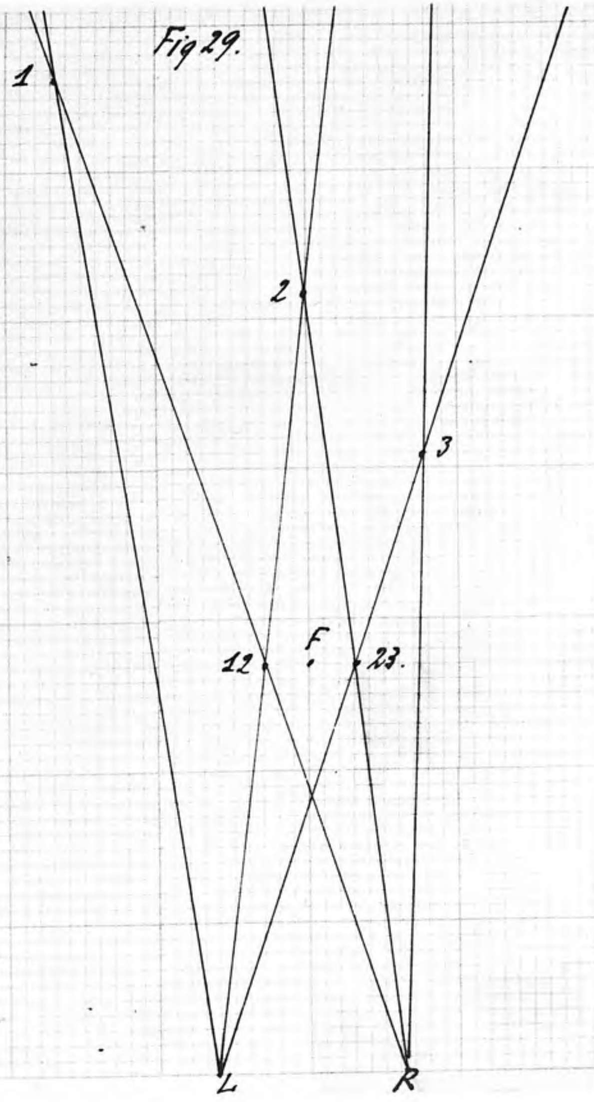


Fig 29.



principles of depth perception of singly seen lateral images both stereoscopic and normal in binocular vision.

When we move the head backwards from the slit we have the impression as if the stereoscopic images moved towards us in relation to the fixation point. This relative movement is illustrated by fig.27, and is in the opposite direction from that shown in fig.11. When we move the head to the left and to the right our impressions are that in the first case the left stereo--scopic image is coming nearer to us and the other re--ceding. In the second case the direction of the movement of the images is reversed. This is illustrated by fig.28 which shows that the direction of the move-ment is opposite to that illustrated by fig.10.

Other striking experiments were carried out. If the angular distances were only of avail for the stereoscopic phenomena one might suppose that the linear distances from the eyes could be different for each rod, and if only the angular distances remained the same there would be no changes in the relative distance of the stereoscopic images which would remain the same as compared with the fixation rod. This could be seen from fig.29. The left rod is at a far greater linear distance than the middle rod, and the right rod much nearer ; in spite of this the stereoscopic images would be seen at the same distance as the fixation rod. This conclusion from the geometrical construction was

Fig. 30.

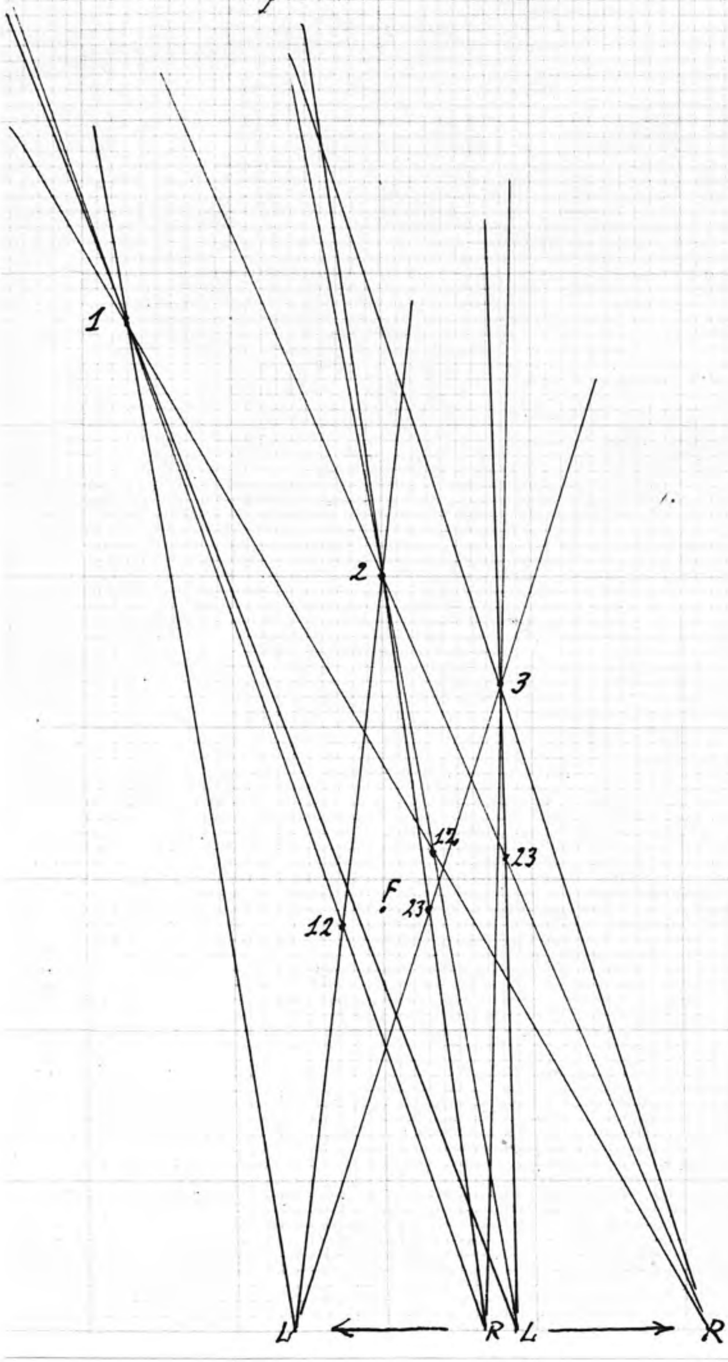
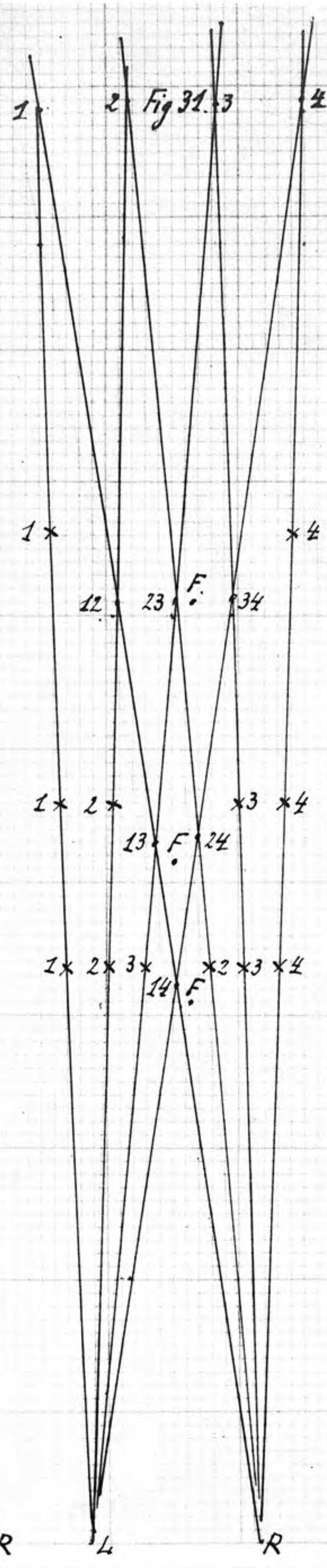


Fig 31.



was confirmed by the experiments. Naturally the monocular images changed their lateral position with respect to the other images, and also the seen distance in the third dimension.

One other phenomenon was also observed. When the head was moved sideways to the left the fixation rod moved behind the left stereoscopic image, and when the head was moved to the right the opposite occured /see fig.30/.

If we increase the number of rods the same depth phenomena can be observed, but the number of the stereo--scopic images grows. Some other similar experiments were carried out which threw light on the investigations of Meyer's wall paper designs. When we placed four rods (Fig 31) at a distance of 21.5 ins. from the eyes and with 1/ in. of the lateral distance from each other, with the fixation rod placed at 14.1 in. we can see three stereoscopic images at the same distance from the eyes and two monocular images further away than the stereo--scopic images. When the fixation rod is placed at a distance of 10.4 in. we see only two stereoscopic images at the depth of the fixation rod and four mono--cular images of four rods further away. In this case the stereoscopic images are formed of the images of rods 1 and 3, and 2 and 4 respectively. At the distance of 8.3 in. of the fixation rod we see only one stereoscopic image formed of the images of the rods 1 and 4, two

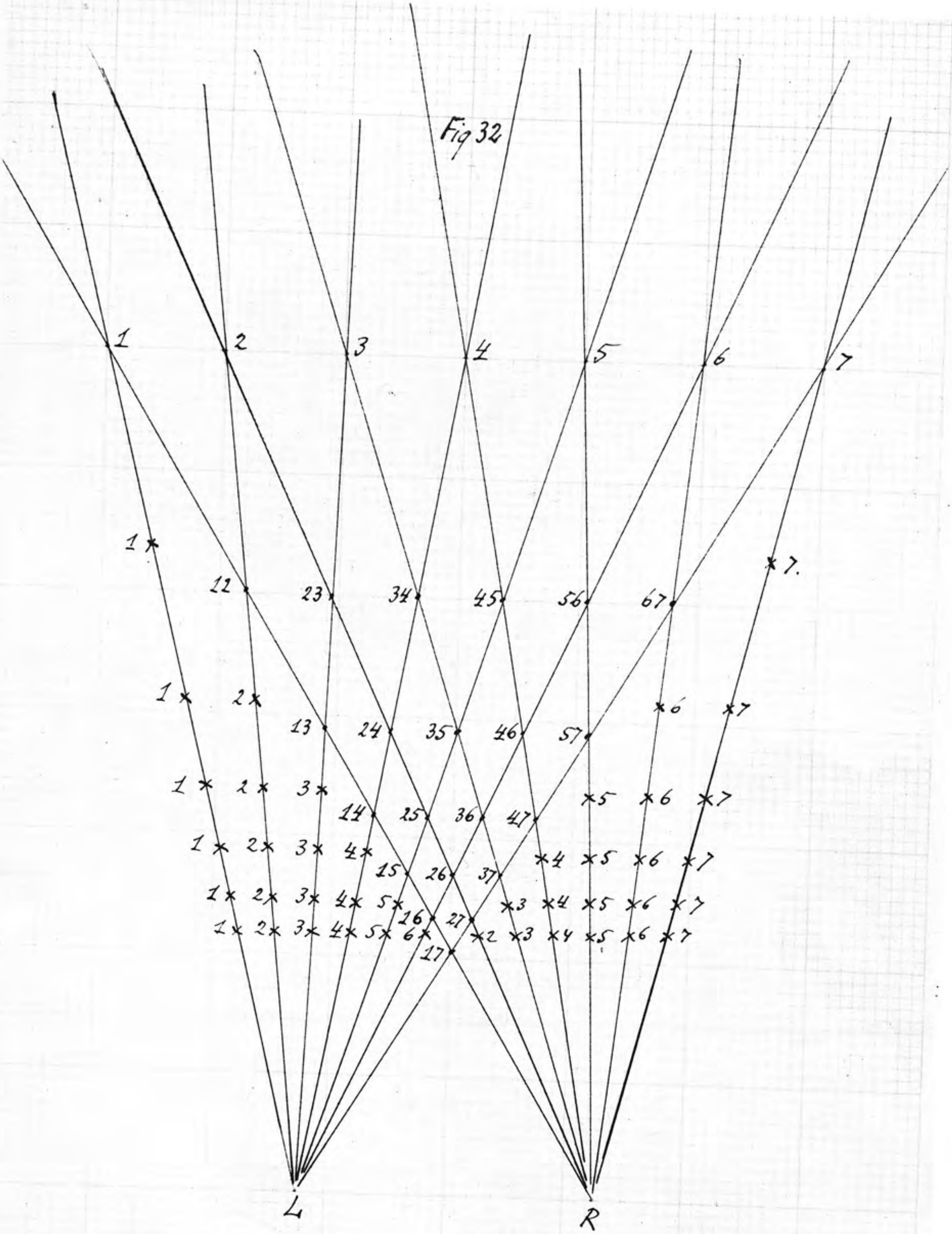

1
2
3
4
5
6
7
12
23
34
45
56
67
13
24
35
46
57
14
25
36
47
15
26
37
16
27
17
L
R

Fig 32

two monocular images of the rods 1 and 4, and two double images of the rods 2 and 3. If we move the fixation rod still nearer towards the eyes we see no more stereoscopic images but four double images of all the four rods.

It is to be remarked that in this last case the fixation point was not in the range of accommodation for one of the subjects and was seen blurred by him especially in nearer positions, and yet the depth per--ception was very accurate and every even very small change in the position of the rods was perceived as a change in the depth perception of the stereoscopic images in relation to the fixation rod as well as to one another. These changes as well as the corresponding relations to the angular distances were the same as in the previous cases. Fig.32 shows how the depth perceptions are related to the different positions of the fixation points when seven rods are situated at a distance of 7 in. from the eyes, and of 1 in. between two adjacent rods. This case is an illustration and to some extent an explanation of the Meyer's wall paper phenomena.

One could not perceive however with any great accuracy if the stereoscopic images were coming nearer with the nearer fixation points ; in any case they were not approaching in the proportion to the changes of the distance of the fixation point, and the perception of the objective distance was not very distinct although all the relative changes in the depth were very distincttly observed if even small changes of positions of the rods

TABLE X.

Stereoscopic phenomena with three rods

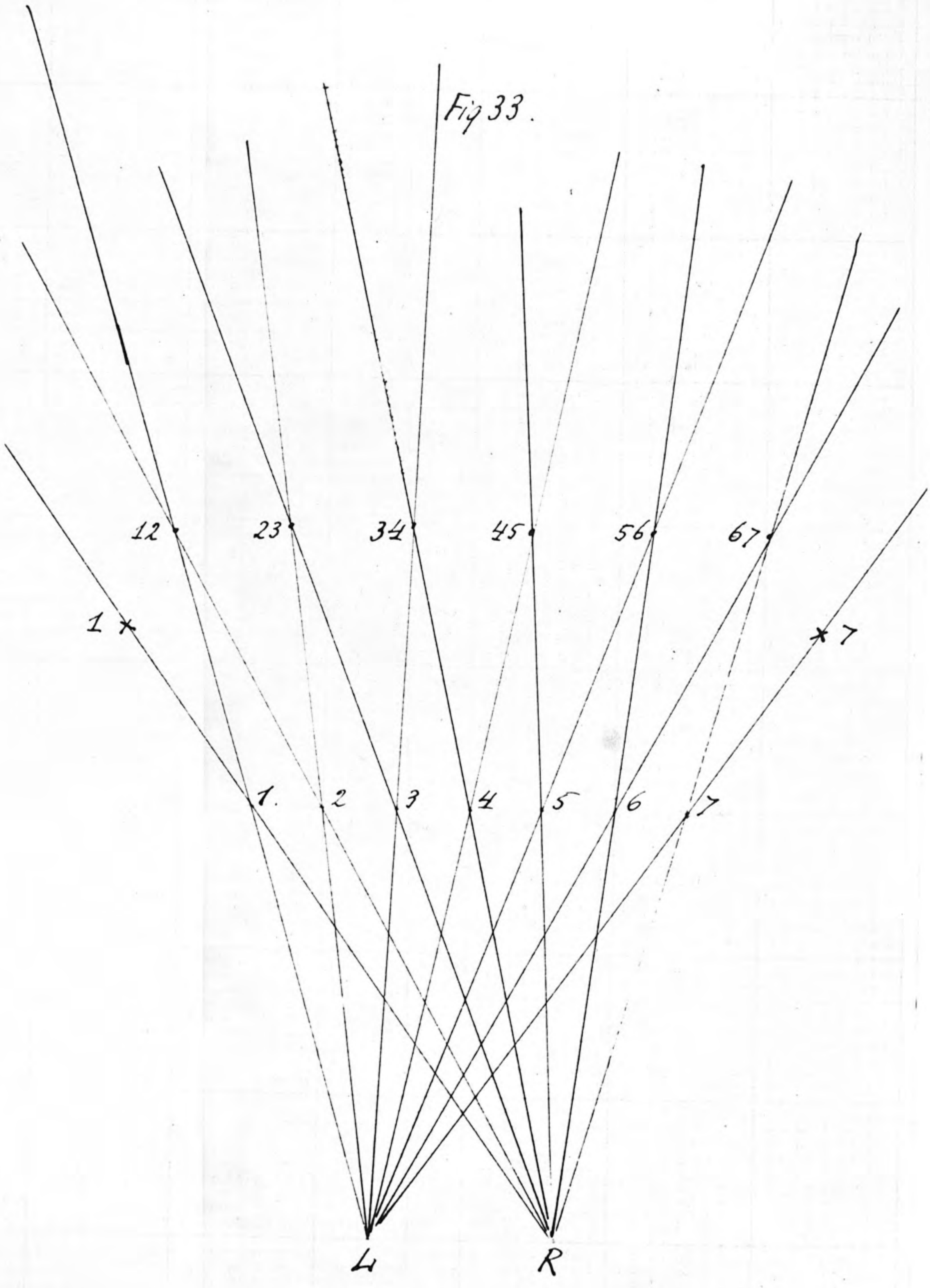
and far fixation point.

Distance of the 3 rods from the eyes.	Lateral distance between the rods.	Distance of fixation rod from the eyes when seen equidistant with stereoscopic images.
10.8 inches	1.2 inches	21.7 inches
11.2 "	1.1 "	20.7 "
14.3 "	1.37 "	34.0 "
15.0 "	1.5 "	37.3 "

Distance of the 3 rods from the eyes.	Lateral distance between the rods.	Stereoscopic images seen relatively to fixation point at 34 ins.
14.3 inches	1.25 inches	nearer
14.3 "	1.37 "	Equidistant
14.3 "	1.5 "	Further

If the distance of the rods from the eyes is kept constant while the lateral distance between them is decreased then the distance of the stereoscopic images from the eyes decreases. If the lateral distance between the rods is kept constant and their distance from the eyes is increased then the distance of the stereoscopic images also increases.

Fig 33.



rods were made.

The inverse experiments were also carried out. They consisted of placing the fixation rod behind the rods to be seen in stereoscopic images. $T_a$ble X shows several experiments and the relations between the lateral and the depth distances of the rods, and the positions of the fixation rod. Fig.33 indicates how these relations could be calculated, The stereoscopic and the monocular images in this case appear much thicker and much more apart from each other than in the case when the fixation rod is placed nearer tothe eyes. Here all the relations are reversed but the angular formula remains the same. Here we see in the same way as in using all kinds of stereoscopes where the fixation points /imaginary/ are situated behind the objects to be fused stereoscopically.

c.

During all the experiments with stereoscopic vision various observations were made regarding the visual shapes and sizes of the images. In the first experiment with three rods in the median plane and with the fixation of the middle one we noticed that the shape of the two stereoscopic images seemed something like two walls of which the nearer parts were seen nearer than the fixation rod, while the further parts further away. Both were slightly inclined approaching each other at the far end. This phenomenon is illustra--ted in fig.34. The visual angles under which the rods are seen play a part in the explanation of this pheno-

Fig. 34.

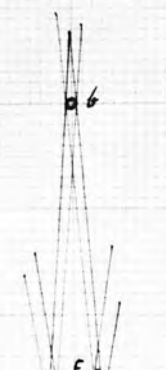


Fig 35

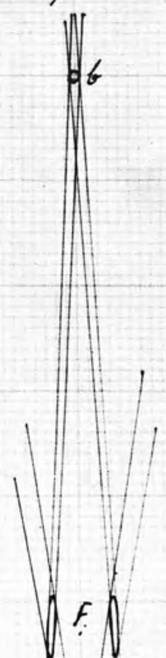


Fig 36.

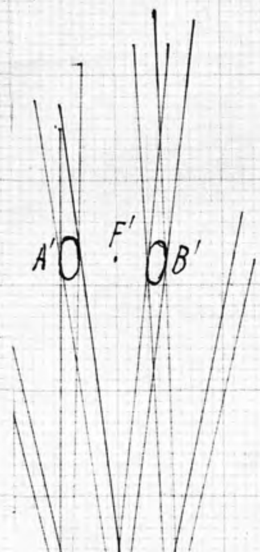


Fig. 37.

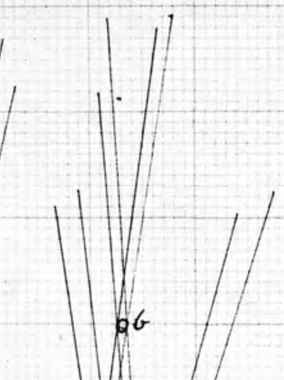
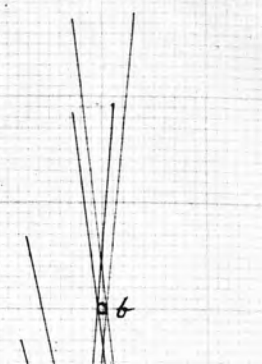


Fig 38.



this phenomenon and therefore they are indicated in the diagram. The visual angle under which the nearer rod is seen is greater than the angle of the further rod, and the greater the greater the distance between the nearer and further rods. A and B give the shapes of the stereoscopic images according to a geometrical construction. These were qualitatively confirmed by observations. In fig. 34 the distance of the nearer rod from the eyes is 8 in. and of the further rod 16 in., in fig. 35 the distance of the further rod is increased to 20 in. while the distance of the nearer rod remains 8 in. This results in a quite noticeable increase in the width of the stereoscopic images A′ and B′ as compared to A and B in fig. 34. These differences were easily observed when the appropriate changes in the geometrical distances of the rods were made.

Fig. 36 illustrates the case of three rods situated in the same plane parallel to the observer's face ; here the visual angles of all rods are practically the same for both eyes and consequently the stereoscopic images A and B are very similar to the monocular images of the rods or to the images when the rods are fixated binocularly : the stereoscopic image of the elongated shape of walls is no longer seen. The lateral distance between all the images seems to be smaller when the fixation point F is in front of the rods, than when it is situated at the same distance as the rods. In the first case the images also look thinner. If we now

Fig 39.

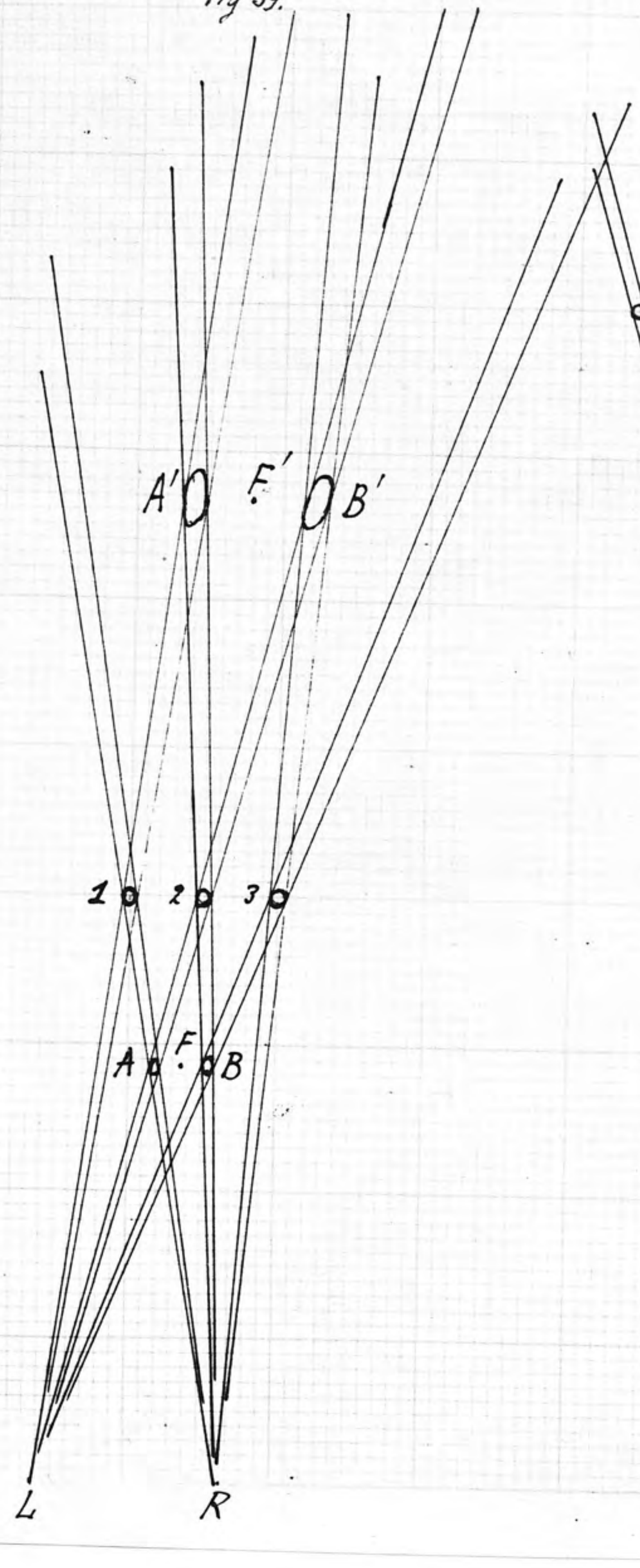
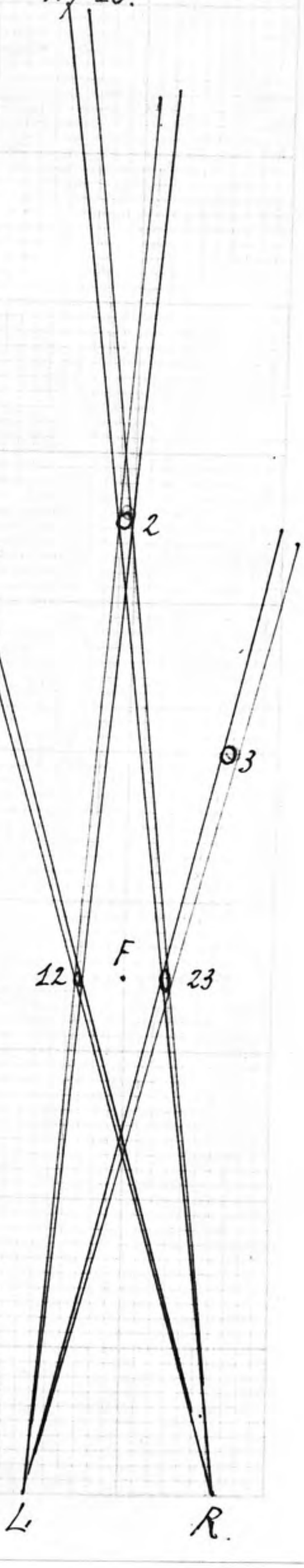


Fig 40.



now change the fixation point to F′ behind the rods the stereoscopic images A′ and B′ appear much bigger than the images A and B, and their lateral distance is also greater. This was also verified by observation. In all cases described till now the rods were placed symmetri--cally with respect to the median visual plane.

When the head of the observer or one of the rods is moved sideways both changes in the distance and of the shape of the images occur. Fig.37 represents the case in which the head has been moved slightly to the left, and fig.38 the case in which the nearer rod was moved to the right. In both these cases the right stereoscopic image comes nearer and the left stereoscopic image moves away from the observer. At the same time the left image grows in size in comparison to the right stereoscopic image. In the case shown in fig.39 there is no appreciable difference in the shape of the two stereoscopic images, both in the case when the fixation point is in front of the rods and behind them.

Fig.40 represents the case when the three rods 1, 2, and 3 are placed at different distances from the eyes. Rod 1 is further and rod 3 nearer than rod 2, but the angle subtended by rods 1 and 2 at the right eye is equal to the angle subtended by the rods 2 and 3 at the left eye, which is the condition that the two stereoscopic images should be seen at the same distance as the fixation point F. Rod 1 is seen here under a much smaller visual angle, and rod 3 under a greater angle

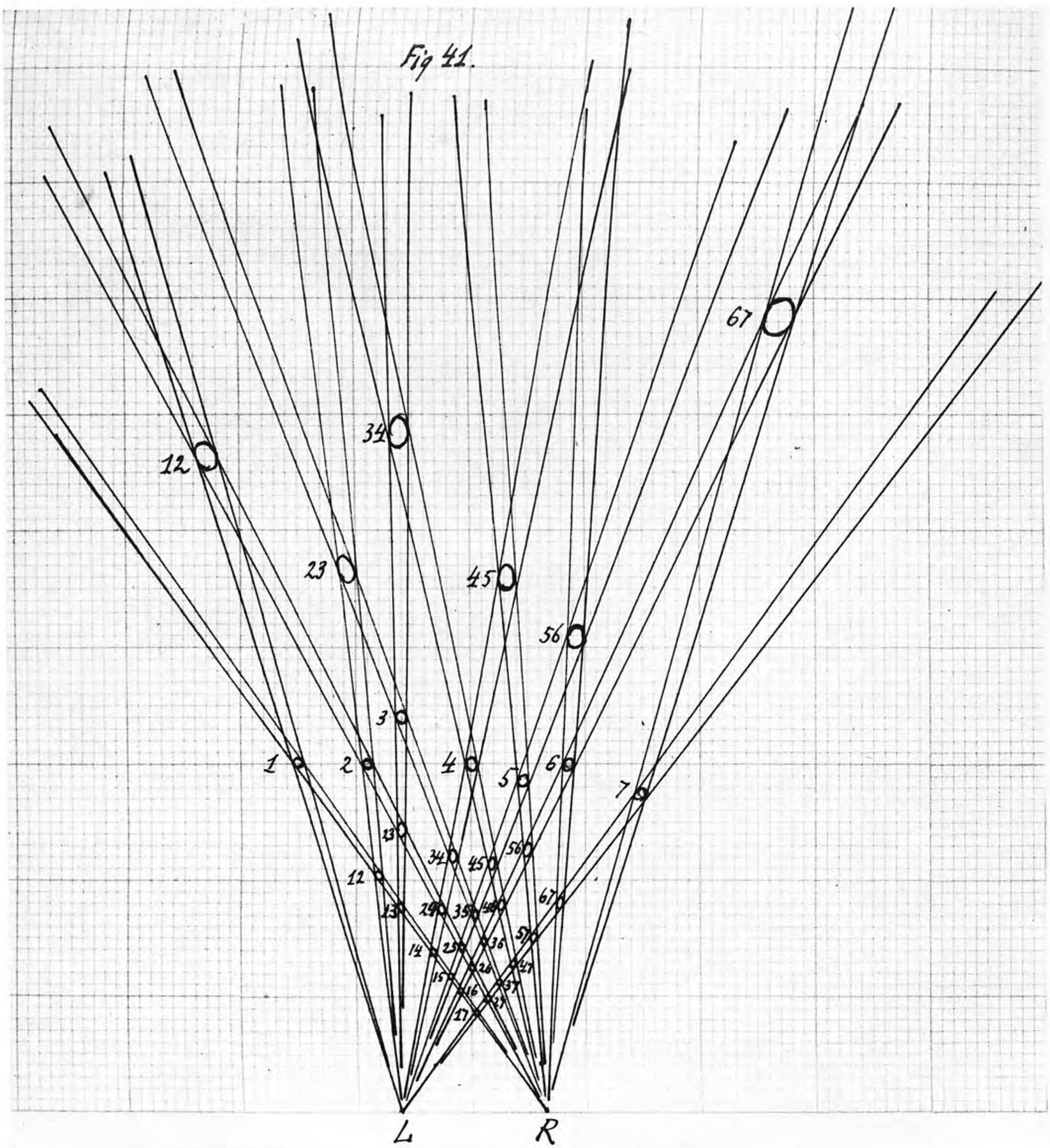


Fig 41.
12
34
67
23
45
56
3
1
2
4
5
6
7
13
34
45
56
12
67
L
R

angle than rod 2. The image 12 appears smaller than 23, and the shapes of both images are different from those in fig.39, as may be inferred from the geometrical construction of fig.40. The left wall is shorter than the right wall. In the fig.41 seven rods are placed at various distances from the eyes and from each other while the approximate distance of the rods from the eyes is 6 in. The figure shows the influence of such variations on the depth perception of the respective stereoscopic images. This case illustrates the stereo--scopic method used in distinguishing between forged and genuine banknotes or between forged and genuine editions of a book.

Until now we have been dealing only with the objects in the shape of vertical rods. But the stereoscopic phenomena can also be observed when horizontal objects are fused stereoscopically. Thus when we have in the same horizontal plane in front of one eye two straight lines of different lengths, and in front of the other eye two lines of the same length but in opposite order, the stereoscopic image resulting from this arrangement is formed by two lines twisted in different directions about some vertical axis. The figs.42 and 43 show that the same principles and the same angular relations apply in this case. It is understood that the lines AB and A′B′ are placed in the same horizontal plane as are CD and C′D′ respectively; and the lines CD and C′D′ are placed below the lines AB and ABB′. Also the

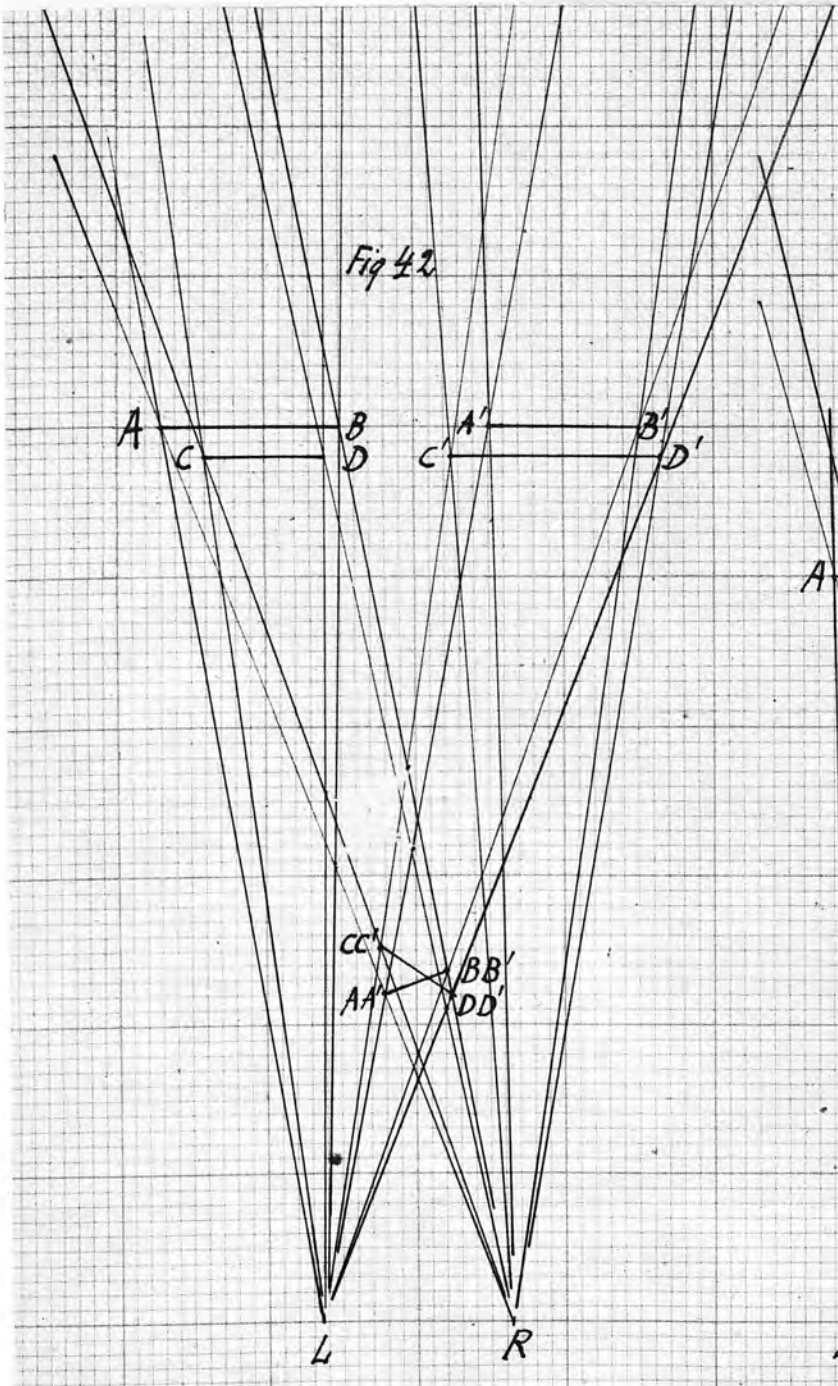


Fig 42

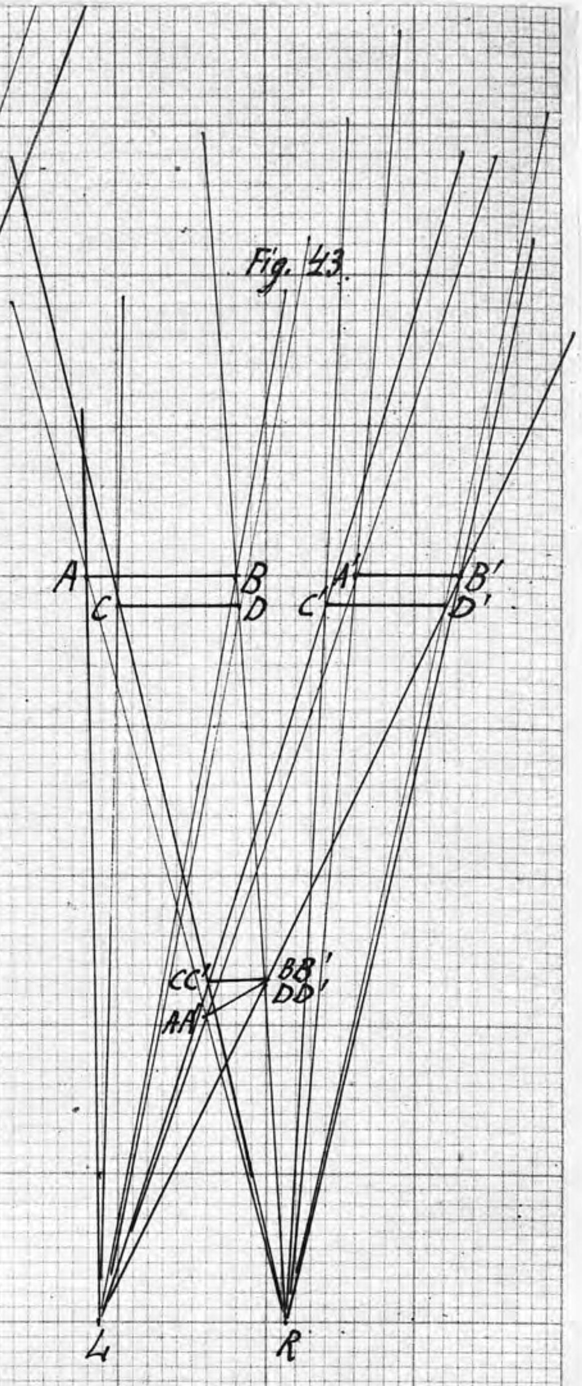


Fig. 43

the stereoscopic lines AA′-BB′ and CC′- DD′ are lying in the horizontal planes, and AA′- BB′ above CC′- DD′. They are twisted as approximately shown in fig.42 round the line or rod perpendicural to the horizontal plane of vision, and which might serve as the fixation point. Figs.42 and 43 differ from each other in this respect that in the fig.42 the axis round which the lines are twisted is placed somewhere in the middle, and in the fig.43 at the right end ; This results from the fact that in fig.43 the visual lines connecting the eyes with the points B and D as well as B′and D′ lie in the same vertical planes.

3.

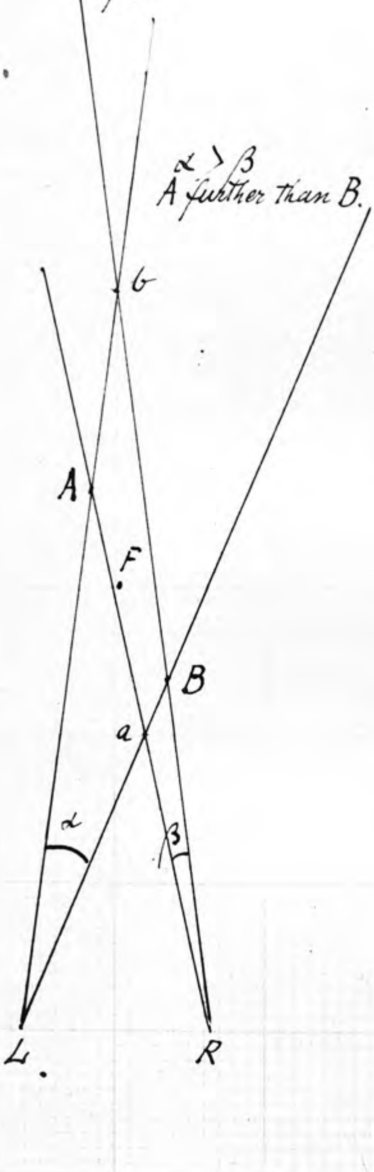
General laws of the depth perception of stereoscopic images.

This description of the investigations on the stereoscopic images shows the succesive phases of experiments which started from the example of the "walls" phenomena and arrived at the generalisation of the depth perception of stereoscopic images and to the angular relation between the monocular vision and the depth perception of the stereoscopic images.

The general laws of the location of the stereo--scopic images can be formulated as follows :

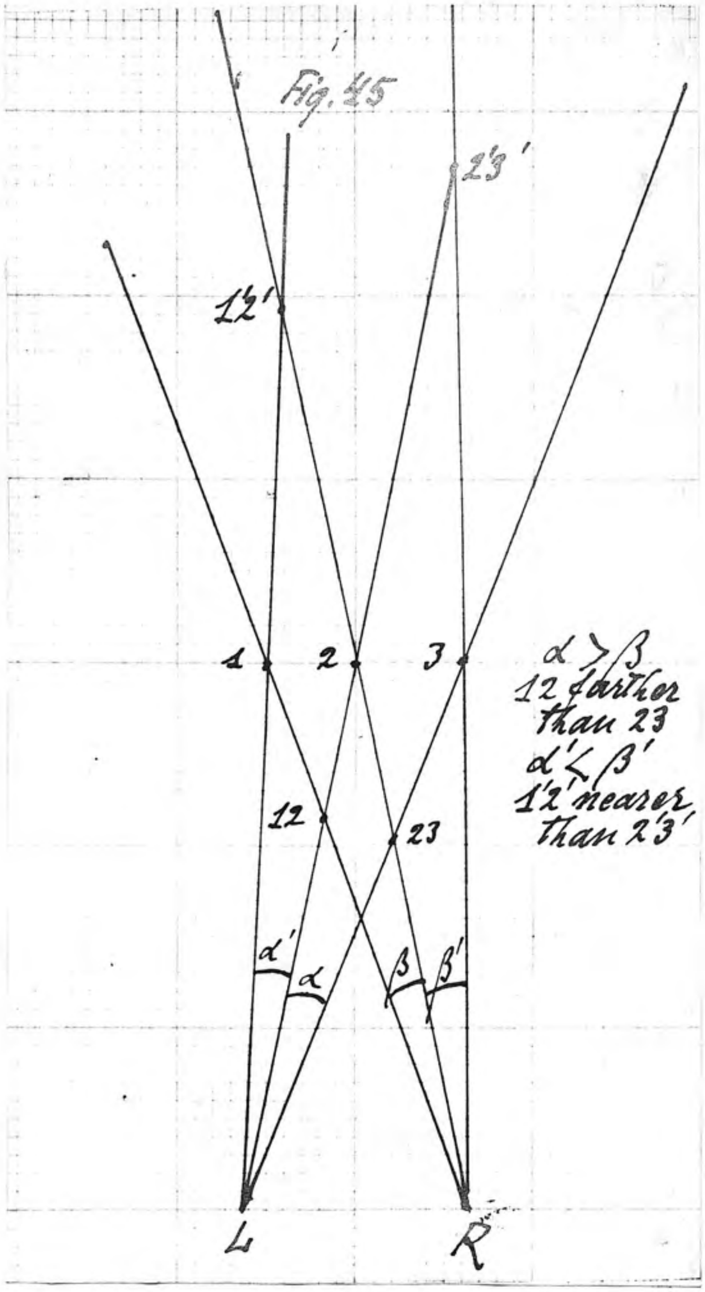
1/ The stereoscopic images are seen at the points

Fig 44



α > β
A further than B.
b
A
F
B
a
α
β
L
R

Fig. 45



2'3'
1'2'
1
2
3
α > β
12 farther than 23
α' < β'
1'2' nearer than 2'3'
12
23
α'
α
β
β'
L
R

points of the intersection of the two pencils of light rays connecting the objects fused in the stereoscopic images with the appropriate eyes. This position has no absolute depth value, but can be determined by placing a fixation point at such a position that the stereoscopic image is seen equidistant with it. In this case they both must lie on the horopter i.e. they subtend equal angles at the eyes. Also if the angle subtended by the stereoscopic image at the eyes is greater than the angle subtended by the fixation point the stereoscopic image is seen nearer than the fixation point and vice versa. The same applies to the differences in the depth perception between any two stereoscopic images /see figs.21, 22, and 24/, and also to the depth perception of singly seen lateral objects in binocular vision /fig.25/.

2/ The relation between the depth perception of the stereoscopic images and the position of objects seen monocularly can be expressed as follows : When the angle subtended by two objects seen monocularly at the right eye is greater than the angle subtended at the left eye by objects which are fused in stereoscopic images with the monocular objects of the right eye, the right stereoscopic image is seen further away than the left stereoscopic image, and vice versa. If these angles are equal the two stereoscopic images are seen equi-distantly /see figs.44 and 45/. This applies also to the singly seen lateral objects in binocular vision

vision /fig.25/.

3/ The greater these differences of the angular distances of the monocularly seen objects the greater also are the differences in the depth between the stereoscopic and the singly seen binocular images. If these differences exceed certain limits the single images cease to be seen and the double images appear; the depth perception of these double images is different from that of the stereoscopic and single binocular images.

The examples shown in the figures illustrate also the relation between the perceived distances and the geometrical position of the objects.

The relation existing between the perception of distance and the physiological processes and especially of what occurs on the retinas is yet to be investigated more thoroughly. But one can advance the hypthesis that the most logical explanation of the stereoscopic phenomena is given by Hering's theory, where disparity of the retinal images provided a basis of explanation of the depth perception in binocular vision. It could be applied to the stereoscopic and single binocular vision with more justification than to the double images as I have tried to show in one of the preceding chapters of this paper.

The retinal disparity is connected in the first place with the changes in convergence of both eyes, and in this sense the binocular vision of depth of of stereoscopic and normal single binocular images in indirect vision might be related with the convergence of the eyes. This has nothing to do with the sensations of muscular efforts connected with the convergence.

III

SUMMARY.

The main results of the investigations on the visual space perception described in this paper may be summed up as follows :

1/ A relation exists between the monocular and the binocular depth perception in indirect vision. This relation can be formulated in the following way. The depth perception of the double images in binocular vision is principally the same as that of monocular images seen indirectly. The differences in depth perception are related to the changes of accommodation of the eye /eyes/ which cause changes in the shape, size, and distinctness of the retinal images to which also the depth perception is related.

2/ The depth perception in indirect vision varies with the wavelength of light used and therefore with the refractive index of light in the media of the eye, in monocular as well as binocular vision in such a way that with the increasing wavelength of light used the seen distance of the object decreases. However, when the colour filters are used the conditions of vision are much more complicated on account of various changes

changes occuring in the field of vision due to eye rivalry, colour mixture, eye dominance, differences between the eyes, etc.; nevertheless here also there seems to exist a relation between the depth perception and the changes in the distinctness of the double and monocular images caused by the changes in the accommo--dation. In this case also the similarity between the monocular and double images exists. But some differences were observed due to the causes mentioned above. In the case of double images more frequent changes /inversions etc./ were observed making the images less steady than with the monocular vision.

3/ The relation between the angular positions of objects viewed monocularly and the depth perception of stereoscopic and single binocular images was establi--shed.

4/ The depth perception of the stereoscopic images is much more stable than that of the double and monocular images, and the changes in the distinctness do not play such an important part in this case. The inversions and the so called illusions are rare in stereoscopic images.

5/ The depth perception of stereoscopic and single binocular images is connected with the changes of convergence which cause the changes in the angular distances of the images viewed monocularly.

I wish to thank Professor James Drever for giving me the opportunity to conduct these investigations at the Laboratory of the Department of Psychology at the University of Edinburgh, and for many helpful suggestions in connection with this work.

I thank Dr. Mary Collins for showing her interest in this work and her kind participation in several experiments.

I also thank Misses and Messrs. B.C.Asthana, K.R.Baldwin, M.R.Birney, J.Black, D.Brown, W.P.Colquhoun, D.S.Finlayson, S.J.Hailey, J.Hardie, M.Henderson, E.F.Hvistendahl, N.E.Loveless, J.E.MacDonald, R.W.Marriott, B.Mounfield, G.Preston, J.M.Ratcliffe, K.H.Rowe, R.Sergean, N.Solomons, J.H.Symons, T.E.Watson, and H.R.Weaver who kindly served as subjects in these experiments, as well as my daughter Dr. Barbara Zając for helping me to carry out some observations on myself.

REFERENCES

1/ Franciscus Aquilonus, Opticorum libri sex, Antwerpiae, 1613.

2/ J.W.Baird, The influence of accommodation and convergence upon the perception of depth, American Journal of Psychology, 1903.

3/ G.Berkeley, An Essay towards a new theory of vision, 1709.

4/ Dr.M.Boniecka, Les courbes de repère de la vision monoculaire dans la lumière homogène, Travaux du Laboratoire de psychologie experimentale de l'Université de Cracovie, Paris, Félix Alcan, 1923.

5/ Edwin G.Boring, Sensation and perception in the history of experimental psychology, New York, 1942.

6/ B.Bourdon, La perception visuelle de l'espace, Paris, 1902.

7/ Sir David Brewster, The stereoscope, its history, theory and construction, 1856.

8/ Harvey Carr, Ph.D. with the coöperation of Jessie B.Allen,Ph.D., A study of certain relations of accommo-dation and convergence to the judgment of the third dimension, The Psychological Review, 1906, Vol.13.

9/ Dartmouth Eye Institute, Hanover, New Hampshire, October 1946, Some demonstrations concerned with the origin and nature of our sensations.

10/ Hugh Davson, The Physiology of the Eye, London, 1949.

11/ F.D.Donders, Die Projection der Gesichtsersheinungen nach den Richtungs-linien, Archiv für Ophtalmologie, Vol.17, 1871.

12/ W.Einthoven, On the production of shadow and perspective effects by difference of colour, Brain, Vol.16, 1893.

13/ James J.Gibson, The perception of the visual world, The Riverside Press, Cambridge, Massachusetts, 1950.

14/ Vernon, W.Grant, Accommodation and convergence in visual space perception, Journal of Experimental Psychology, Vol.31, 1942.

15/ V.Grzybowski, De la vision monoculaire de l'espace, Bulletin de l'Academie des sciences de Cracovie, 1910.

16/ Hamilton Hartridge, Recent advances in the physiology of vision, London, 1950.

17/ W.Heinrich, On monocular visual space, British Journal of Psychology, vol.III

18/ W.Heinrich, Le probleme psychologique de l'espace, Travaux du Laboratoire de Psychologie experimentale de l'Université de Cracovie, Academie Polonaise des Sciences et de Lettres, Paris, Félix Alcan, 1923.

19/ H.v.Helmholtz, Uber den Horopter, Archiv für Ophtalmologie, vol.10, 1864.

20/ H.v.Helmholtz, Handbuch der physiologischen Optik, Zweite umgearbeitete Auflage, Hamburg und Leipzig, 1896.

21/ E.Hering, Beiträge zur Physiology, 1861 - 1864.

22/ E.Hering, Das Gesetz der identischen Sehrichtung, Reichert und Du Bois-Reymonds Archiv, 1864.

23/ E.Hering, Die Gesetze der binocularen Tiefen wahrnehmung, Reichert and Du Bois-Reymonds Archiv, 1865.

24/ E.Hering, Der Raumsinn und die Bewegungen des Auges, Handbuch der Physiologie der Sinnesorgane, Leipzig, 1879.

25/ F.Hildebrand, Das Verhältnis von Accommodation und Konvergenz zur Tiefenlokalisation, Zeitschrift für Psychologie, 1894.

26/ William H.Ittelson and Adelbert Ames,Jr., Accommo-dation, Convergence and their Relation to apparent Distance, The Journal of Psychology, 1950

27/ Dr.E.R.Jaenisch, Über die Wahrnehmung des Raumes, Zeitschrift für Psychologie und Physiologie der Sinnes-organe, Leipzig, 1911.

28/ K.Koffka, Principles of Gestalt Psychology, London New York, 1935.

29/ J.Kurtz, On the fluctuations of reciprocal position,of two points in the monocular field of vision, British Journal of Psychology, vol.3,

30/ St.Loria, Dela vision latérale, Bulletin de l'Academie des Sciences de Cracovie, 1906.

31/ Meissner, Beiträge zur Physiologie des Sehorgans, Lepzig, 1826.

32/ H.Meyer, Über einige Täuschungen in der Entfernung und Grösse der Gesichtsobjekte, Archiv für physiologische Heilkunde, 1842.

33/ Nagel Albrecht, Das Sehen mit zwei Augen und die Lehre von den identischen Netzhautstellen, Heidelberg und Leipzig, 1861.

34/ Nagel Albrecht, Uber die ungleiche Entfernung von Doppelbildern, die in ungleicher Höhe gesehen werden, Archiv für Ophtalmologie, Bd.8, 1862.

35/ P.L.Panum, Physiologische Untersuchungen über das Sehen mit zwei Augen, 1858.

36/ P.L.Panum, Die scheinbare Grösse der gesehenen Objekte, Archiv für Ophtalmologie, Berlin, 1859.

37/ R.A.Pfeifer, Uber Tiefenlocalisation von Doppel--bildern, Leipzig, 1906.

38/ Schultz, Uber physiologische Gesichts-und Farben--erscheinungen, Schweigerts Journal für Physik und Chemie, 1816.

39/F.Schumann, Beiträge zur Analyse der Gesichtswahr--nehmungen, Zeitschrift für Psychologie, 1900, 1902, 1904.

40/ R.Thouless, The general principle underlying effects attributed to the so called phenomenal constancy tendency, Psychologishe Forschungen, Bd.19, 1934.

41/ E.B.Titchener, Experimental Psychology, 1901.

42/ E.B.Titchnerk, A textbook of Psychology, 1910.

43/ A.Tschermak und P.Hoefer, Uber binoculare Tiefen-wahrnehmung auf Grund von Doppelbildern, Archiv für die gesammte Physiologie herausgegeben von Dr. R.T.W. Pflüger, 98 Bonn, 1903.

44/ M.D.Vernon, The perception of distance, British

British Journal of Psychology, vol.XXVIII, July and October, 1937.

45/ Dr.Anna Vicholkovska, Illusions of reversible perspective, Psychological Review, vol.13, 1906.

46/ Leonard de Vinci, Traite dela Peinture par P.M. Gault de Saint-Germain, Genève, 1820.

47/ M.Werheimer, Experimentelle Studien über das Sehen von Bewegung, Zeitschrift F6r Psychologie, 61, 1912.

48/ Kurt Wilde, Der Punktreiheneffekt und die Rolle der binocularen Querdisparation beim Tiefensehen, Psycho--logishe Forschung, Bd.23, 1950.

49/ R.S.Woodworth, Experimental Psychology, 1938.

50/ W.Wundt, Beiträge zur Theorie der Sinneswahrnehmung, 1862.

51/ J.Zając, Der verticale Schnitt des monocularen Sehraumes, Bulletin international de l'Academie des Sciences de Cracovie, 1911.

52/ J.Zając, La localisation en profondeur des images doubles, Travaux du Laboratoire de Psychologie Experimentale de l'Université de Cracovie, Paris, Félix Alcan, 1933.