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STEREOSCOPIC VISION APPLIED TO PHOTOGRAMMETRY

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ABSTRACT

In Part I the visual processes involved in depth perception are briefly described and discussed, while in Part II their application in stereo plotting and allied observations is considered. Reference is made to the visual axis, the need for and nature of eye movements, the conception of the horopter space within which fusion of the binocular images occurs and objects are seen in three-dimensions, and the tolerances for fusion implied by the existence of Panum's areas. Monocular clues make an important contribution to the perception of depth, and the apparent location of an object in space is determined by the factors of retinal disparity, convergence, angular size, perspective, motion parallax, elevation, aerial haze, etc. The following problems are then discussed: The significance of the horopter in relation to the general contour in a stereo photograph; the fusion of the images in a stereo plotting machine; the arguments for and against some convergence of the eyepiece axes; the special problems of spectacle wearers; the functions of field stop. An analysis of the visual task in contour plotting is attempted, but a more complete analysis would be possible if records were available of the observer's eye movements while plotting. Finally, chromatic aberration in relation to the Multiplex system is considered, and also in connection with the stereoscopic effect observed with differently coloured objects lying in a plane.

PART I: STEREOSCOPIC VISION

The Optical System of the Eye; the Visual Axis; Eye Movements

Fig. 1 shows a horizontal section through the human eye and illustrates its refracting system comprising the cornea and crystalline lens, the ciliary processes controlling the focusing power of the lens, the iris which controls the cone of light focused by the lens, and the light-sensitive membrane, the retina, lining the inner wall of the eyeball and on which the image is focused. The detailed structure of the eye is dealt with exhaustively in text-books on physiological optics and need not detain us here. (See, for example, Duke-Elder, *Text-book of Ophthalmology*, Vol. I, 1932.)

For our purpose it is of interest to contrast the eye with three other types of optical device—the telescope, the camera, and the sky lens. The telescope

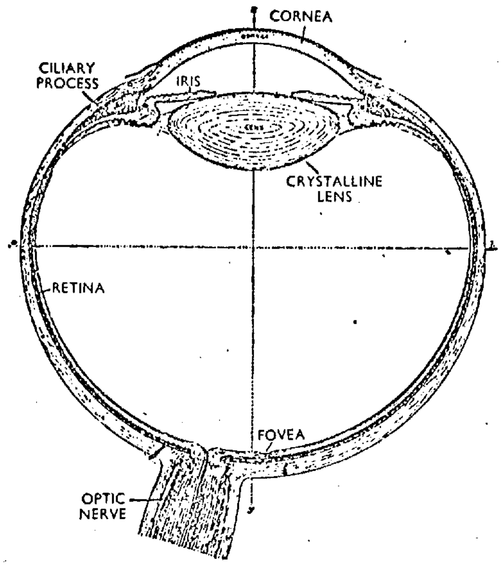

*Fig. I. A horizontal section of the human eye.**

can be used to study the fine detail of a distant object, but as it normally has a rather small field of view of perhaps only a few minutes of arc, it has to be deliberately directed to each point in the scene which it is desired to examine in detail. On the other hand, the average camera covers a much wider field of, say, 50°, and both the definition of the image and the distribution of the light-sensitive silver halide grains are essentially uniform over the area of the plate or film. The sky lens is a specially designed optical system for photographing the clouds in the sky, and receives light from very nearly the whole hemisphere of the sky in one photograph.

The eye is rather remarkable in sharing some of the properties of both the sky lens and the telescope. The lens and retina are capable of collecting light from a field of slightly more than 180°, and it is only the obstructions of the face—nose, cheek, forehead, etc.—which reduces this angle of acceptance for a single eye. The two eyes together do, in fact, cover a field slightly in excess of 180° in the horizontal plane. On the other hand, if the fine detail of any point in the scene is to be examined, then the observer has to direct his eyes to the point under regard. The resolving power of the retina has its maximum at the fovea (see Fig. I) and a line through the foveal centre and the nodal point defines the visual axis of the eye (Fig. II), which has to be directed to the point of interest at any given moment. The details of the whole scene are then only perceived as a result of the rapid movements of the eye darting from one point of the scene to another.

This pointer-like property of the eye is well brought out by measurements of the resolving power of the eye at various angles from the visual axis leading to the curve shown in Fig. III. The peripheral retina does, of course, con-

*(From Schafer (3) Quain's Anatomy, vol. III, Pt. III. 10th Ed. Longmans, Green and Co., London 1894.)

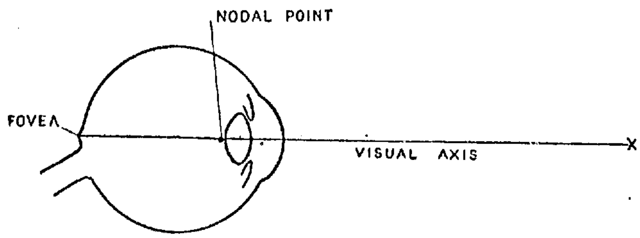

Fig. II. The visual axis of the eye.

tribute to the perception of the general pattern of the scene, and it also has other very important functions, such as enhanced sensitivity to movement, and high light-sensitivity when the eye is dark-adapted and so on.

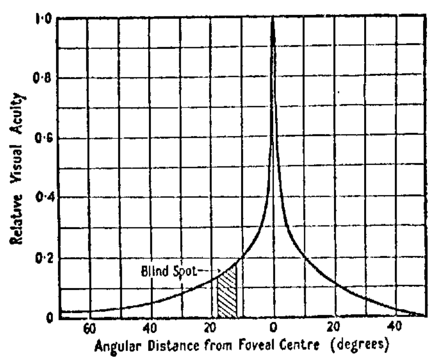

Fig. III. The variation of the visual acuity across the retina.

The movements of the eyes necessitated by the existence of the visual axis are themselves of great interest and in all probability of fundamental importance to visual perception. There are, in fact, two or three distinct types of movement: there are, first, the small movements which occur even when a small fixation target is being viewed as steadily as possible and which imply a limited precision to the location of the visual axis; then there are the saccadic movements in which the eye moves in a series of jumps and pauses; such movements occur not only when viewing a scene but in reading, for the eyes make a number of fixation pauses along each line of print. Lastly, there are the pursuit movements in which the eye makes a relatively smooth continuous movement when following a moving target. Examples of these three types of movement are shown in Fig. IV as recorded by a corneal reflex method. (Lord, 1948; Lord and Wright, 1948, 1949, 1950.)

Binocular Vision

One obvious advantage of having two eyes is the increase in the field of view. Fig. V shows that while some 120° of the central field is covered by both eyes, the last 30° on either side of the peripheral field in the horizontal plane is observed monocularly. In this diagram it is assumed that attention

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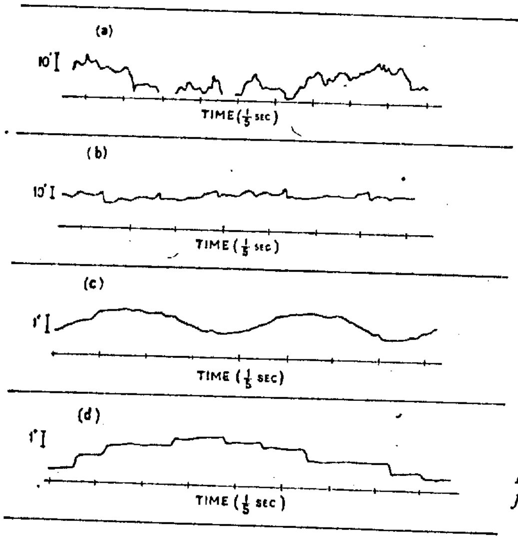

(*a*) Movements during fixation on a target when the observer was unable to maintain very steady fixation.

(*b*) Movements during fixation on a target when the observer was able to maintain very steady fixation. (The effect of small head movements are also included in this record.)

(*c*) Pursuit eye movements while the observer was following a target attached to a swinging pendulum.

(*d*) Saccadic eye movements recorded when the observer was attempting a slow, continuous sweep movement between two targets without any moving target to follow.

Time is recorded horizontally in 1/5ths second. The scale of the angular deflection is indicated by the short vertical line to the left of each record.

Fig. IV. Eye movement traces as drawn from records by Lord and Wright obtained by a corneal reflex method.

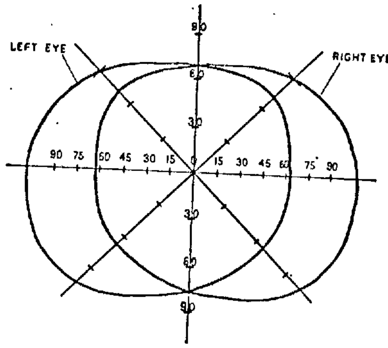

Fig. V. The angular fields of view of the right and left eyes. (The scale of the field is in degrees.)

is being directed to a particular point in a scene (represented by the zero point in the diagram), and convergence of the visual axes on to this point is necessary if double vision (diplopia) is to be avoided. The two foveæ on which the point is then imaged are in fact important examples of what are known as corresponding points.

We can imagine that for each point on one retina there is a corresponding point on the retina of the other eye such that, when both points are stimulated, they give rise to a single fused image in the brain. This conception, as we shall see in a moment, may need to be modified, but on the assumption that corresponding points in the two retinæ are equally spaced from their respective foveæ, Müller's horopter, Fig. VI, can be constructed to give the locus in space of points which will all appear single although viewed by the two eyes. This theoretical horopter is a circle passing through the nodal points of the two eyes and the point under foveal fixation.

Experimental determinations of the horopter are not in agreement with this theoretical curve, and the particular shape that is recorded is a function of the viewing conditions and also to some extent of the concept which is held

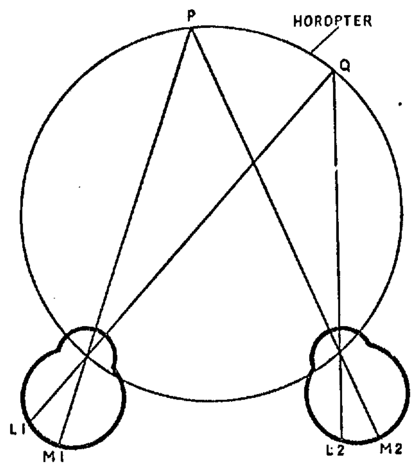

Fig. VI. Müller's hypothetical horopter, as defined by the locus of points appearing single in binocular vision when P is fixated, and assuming that corresponding points in the two retinae are equally spaced from their respective foveal, that is, $L_1M_1 = L_2M_2$.

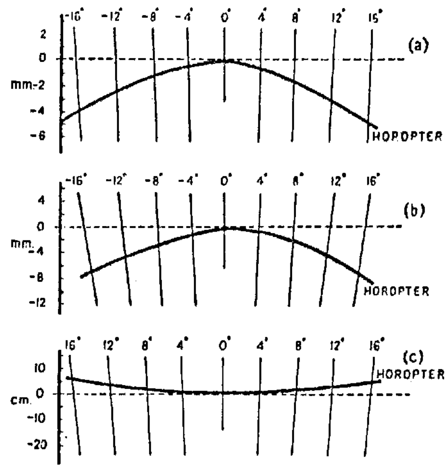

Fig. VII. Experimental determination of the horopter defined as the apparent frontal plane, when a central point is being fixated
(after Ames, Ogle and Gliddon).
Distance of fixation point:
(*a*) 20 *cm.* (*b*) 76 *cm.* (*c*) 2 *m.*
Displacement from frontal plane plotted against angle across field.

to define the horopter. Thus, Fig. VII shows the determination of the horopter regarded as the locus of points lying in a frontal plane perpendicular to the direction of view as measured for three viewing distances and with fixation maintained on a central target in each case. (Ames, Ogle and Gliddon, 1932.)

Fortunately, the direction of the visual axes of the two eyes on to the point of regard does not have to be exact to ensure single vision of the point. Fusion will also be possible for other parts of the visual field provided the images fall near to the corresponding points to within the so-called Panum's area (which is in effect a kind of tolerance area). The size of the Panum areas increases with the displacement across the retina from the fovea, but has an angular diameter of the order of a few minutes of arc at a degree or two from the fovea. Walls (1952) has recently emphasised that the existence of the areas leads to a different concept of the horopter from that of a surface; it should rather be thought of as a space within which all objects will be seen fused and in three dimensions. Objects lying in front or behind the horopter space will appear double, and the horopter space might well be defined as the space outside which objects do appear in diplopia. We should then understand the perception of an extended scene in three dimensions as derived from successive binocular fixations on different points in the scene, at each of which some part of the scene is seen in depth.

Before considering the nature of stereoscopic vision in more detail, we should note the remarkable co-ordination required of the extra-ocular muscles if the orientation of the two eyes is to be correctly maintained during the very rapid fixation movements that occur, even when account is taken of the tolerances allowable on account of Panum's areas. Fig. VIII illustrates the anatomy of the eyes in their orbits and of the extra-ocular muscles which control the eye movements. The degree of co-ordination that is required, not only between the two eyes but between the eyes and the head, is almost incredible, but is nevertheless successfully achieved in persons with a normal oculo-motor system and normal muscle balance.

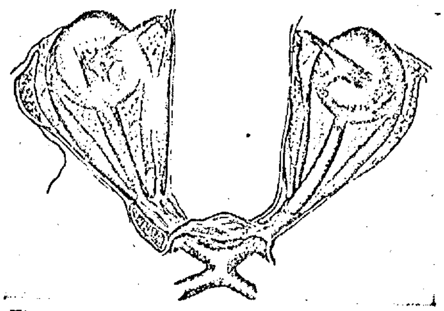

*Fig. VIII. Diagram showing the eyes in their orbits and the extra-ocular muscles.**

The Perception of Depth

The primary clue to distance arises from the binocular parallax associated with the different view-points of the two eyes. Each eye forms a slightly different image of a three-dimensional scene and the retinal disparity that exists for the very simple case of the two object points A and B at different distances from the observer is illustrated in Fig. IX. If this disparity $B_L B_R$ is not excessive the brain will be able to fuse the two images by processes which are only imperfectly understood but which evoke a sense of depth, so that A and B are clearly seen to be at different distances. From what has been said above, it will be recognised that this fusion will occur provided A and B lie within the same horopter space. However, experiment shows that some sense of depth is retained even in diplopia (Wright, 1951). Fusion is not, therefore, an essential element in depth perception, although it must be an important contributory factor.

A normal scene will be vastly more complicated than Fig. IX and will in general involve many objects at various distances from the observer, hence as the scene is scanned by the observer some of the objects will be seen at a given moment fused and in three-dimensions, while others will be seen in diplopia. Then as the fixation is changed, a new part of the field will be seen fused and so on. Just how the relative locations in space of the successive fixation areas are interlocked, is still a matter of dispute, but experiments suggest that the varying convergence of the two eyes as a near or distant object is being viewed, may be an important link (Wright, 1951).

When a single object is seen against an otherwise uniform field (e.g. an illuminated aperture with a dark background), convergence is virtually the only clue to its distance that is available, if we ignore the extremely feeble

*(From Helmholtz (1) Physiologische Optik. 2nd Ed. Leopold Voss, Hamburg and Leipzig, 1896.)

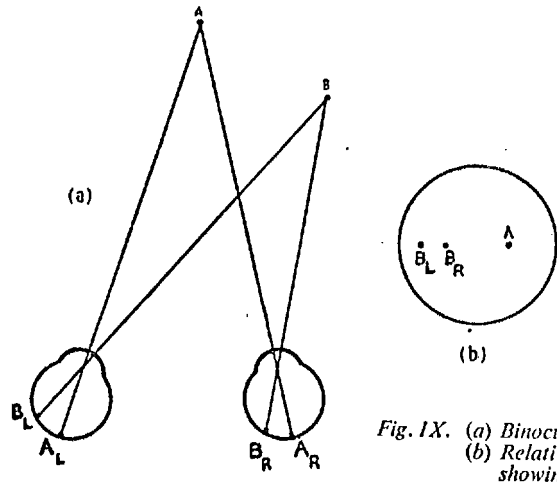

Fig. IX. (*a*) *Binocular viewing of two objects.*
(*b*) *Relative positions of images on two retinae showing disparity* $B_L B_R$.

effect of accommodation, and if there are no subsidiary monocular clues to help, such as a knowledge of the size of the object. Even convergence is a very unreliable factor for the accurate determination of the distance of an isolated object, perhaps because of rapid adaptation to the tension in the muscles, but the simple experiment of observing the apparent change in size of an object when a small-angle prism is held base outwards in front of one eye, so requiring increased convergence for fusion, demonstrates with certainty that convergence is a factor in space perception.

The smallest distance by which one object can be seen to lie ahead of another depends very much on the observing conditions and the nature of the two objects. The highest stereo-acuity will only be attained when the two objects are well illuminated, are sharply defined and clearly contrasted against the background, and are seen close to each other. This last condition ensures that the retinal disparity can be registered with maximum precision using the foveal area of the retina. Expressed in terms of angular disparity, a stereo-acuity of 2 seconds of arc has been recorded under optimal conditions, but if a value of 10 seconds of arc is taken as typical of normal viewing conditions, this implies that for objects 5 ft. from the observer, there are 15 discriminable planes per inch, and 4 discriminable planes per inch at a distance of 10 ft. away. For two objects farther away than about 1,200 yards, it is impossible on the basis of binocular parallax alone to distinguish which is the nearer, however far apart they may be.

Good stereo-acuity may not necessarily be associated with an ability to make accurate estimations of the finite difference of distance between two objects. This calls for a different type of visual dexterity and a different type of training, although no doubt under conditions where the acuity would be poor, the estimation of differences would be reduced also.

Monocular Clues to Distance

It is quite possible to design experiments in which an observer using one eye only virtually loses all ability to discriminate distances. Such experiments, however, are not typical of normal observing conditions, in which monocular clues may contribute quite vitally to depth perception (Gibson, 1950); these clues cannot be ignored in photogrammetry.

There is angular size—the nearer an object, the larger its angular subtense. There is perspective, a factor which is most apparent where some relatively simple geometrical pattern exists, such as the converging of parallel lines or the diminishing pattern of a tessellated pavement. Allied to this is the texture gradient of a surface, in which the texture becomes vanishingly fine as the surface recedes into the distance, whether the texture is made up of chips of a road surface, the lumps of earth in a ploughed field, or the heads of the people in a crowd.

Motion parallax is one of the most important monocular factors bringing out the solidity and three-dimensional character of a real scene as the observer moves his head, and its absence is perhaps the most significant difference between a stereo photograph and a real scene. Other clues are the overlapping of one object by another, the higher elevation of the more distant objects, the information provided by the lighting and shadows, the aerial haze overlaying the distant landscape, the sharply defined, clearly contrasted, near object seen against the hazier distant background and so on.

In a normal scene, the monocular and binocular clues are nearly all present in some degree, and as they are usually in harmony, they combine to produce a most compelling sense of depth and three dimensions. Considered individually, binocular disparity is the primary and pre-eminent contribution, but each factor plays its part. Under special, usually restricted, viewing conditions, any one of them may become the dominant factor, while in trick situations, some of the clues may apparently be in opposition to others. In such circumstances, the brain may require a considerable time to find the solution to the visual problem presented to it.

PART II. APPLICATIONS TO PHOTOGRAMMETRY

General Viewing of Stereophotographs

When large-area stereo prints are being viewed, such as the prints prepared by the anaglyph method in red and blue-green and viewed through correspondingly coloured filters, or by the vectograph method and seen through polaroid viewers, it is interesting to consider the relation of the horopter to the judgment of the relative heights of widely separated objects in the photograph.

When a given point is being fixated, the apparent frontal plane, as already mentioned, may not be a plane normal to the direction of view, and may indeed by a curved surface either convex or concave to the observer, depending on the viewing conditions. This would mean that objects having the same disparity in the photograph would not necessarily appear to be in the same plane. In an aerial photograph of, say, hills and valleys with no auxiliary features which might help to define the horizontal plane, the curvature of the horopter could be a potential source of error in judging any gross curvature or contour changes of the surfaces.

Of course, stereo pictures are not viewed by steady fixation on just one point, but are scanned over their whole area. In that case, no single horopter surface is involved and convergence clues help to interpret equalities and differences of disparities. Most of all, however, the photograph has an edge which in general is a rectangular edge or frame, and perhaps this more than anything else helps to provide a reference plane relative to which the height and depth of the hills and valleys can be compared. The rectangular shape of the frame is not a specifically binocular factor, and we have here an example of a monocular clue—shape or form—playing an essential role in a stereoscopic problem.

Since the viewing of photographic prints under the conditions described here is mainly carried out for qualitative rather than quantitative studies of contours, the problem that has been raised is not of major importance in this context. It is nevertheless of interest and is a useful introduction to an analogous problem in the viewing of stereo-pictures in contour-plotting machines to which reference will be made later.

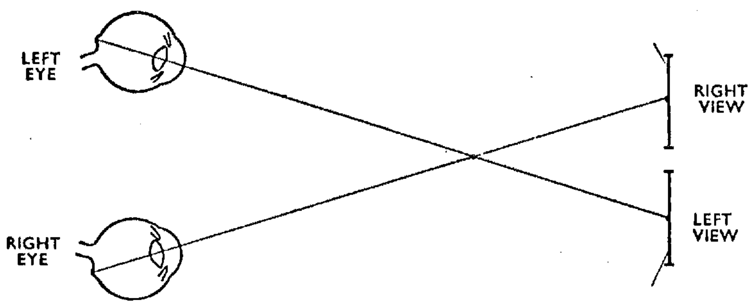

Fig. X. Diagram to illustrate principle of viewing stereo photographs with views transposed.

One further small point may be made in connection with the reproduction of stereo-pairs side by side for viewing in a hand stereoscope. These are normally arranged with the right-eye view on the right and the left-eye view on the left, thus being ready for viewing in a stereoscope. Some people can successfully relax their convergence while maintaining their accommodation and are thus able to fuse and view these stereo-pairs without the aid of any auxiliary optical system. This is a useful attribute which many more people would like to be able to share and could almost certainly do so if the photographs were merely transposed, with the right picture on the left and vice versa. With this arrangement it is only necessary to converge on to a point between the card and the observer, as shown in Fig. X, for the pictures to be correctly fused and seen in relief. This enhanced convergence is relatively easy to produce, especially if the photographs are at first held well away from the observer and he interposes his finger mid-way between himself and the prints, to assist him in attaining adequate convergence. Fig. XI provides a transposed stereo pair on which the reader can make the experiment for himself.

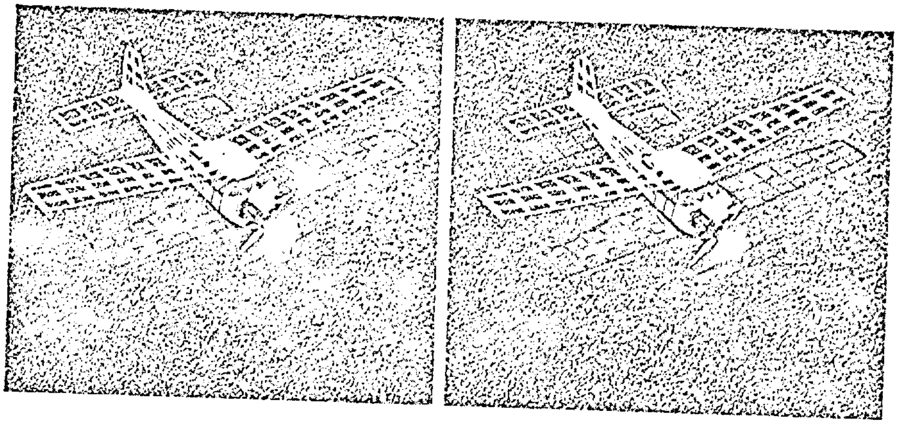

Fig. XI. Transposed stereo photographs for viewing by the principle illustrated in Fig. X.

Binocular Viewing Systems

Many observers find great difficulty in making the two fields overlap and in securing fusion when they look into a binocular instrument such as a binocular microscope. The same is true when people look into the contour-plotting machines used in photogrammetry, although since they are employed on a much more restricted scale, fewer reports of such difficulty are encountered. If the axes of the viewing systems are converging, fusion is more readily secured, and it is evident that the cause of the trouble is an inability to relax the accommodation and the convergence sufficiently for the axes of the eyes to be parallel, the condition required for fusion if the eyepiece axes are parallel.

It is unlikely that there is a simple, or even single, reason for this difficulty, which is apparently associated in some cases with a virtual paralysis of accommodation (Inst. Geo. Nat., 1942). In the case of the microscope, the fact that the observer knows that the object on the microscope stage is close to him gives rise to a natural tendency to converge; indeed, where a binocular microscope is being used as an aid to micro-manipulation, it is necessary that the enlarged image should appear to be located at a point in space near to the operator, otherwise there will be confusion between the sense of touch and the sense of sight. Perhaps the proximity of the eyepieces tends to induce accommodation, and E. F. Fincham has some evidence that the smallness of the field of view may enhance the effect. With instruments such as binoculars, which are used out of doors and on distant objects, fusion difficulties are generally much less pronounced.

Whether provision should be made for the axes of contour-plotting machines to converge is a matter for argument. A period of training in the use of these instruments is always necessary, and one of the aims of the training is to develop greater freedom and flexibility of the accommodation and convergence. After such training, fusion becomes easy, and it can be argued that, since relaxed accommodation and convergence are the generally acknowledged conditions for minimum visual fatigue, parallel optical axes of the eyepiece system are correct for prolonged use of the equipment. On the other hand, since this tendency towards convergence does exist with some observers when first using the apparatus, it may be that the most restful condition for them would be at least a slightly converging system.

Since the contour observations involve only relative settings between the target and the aerial photograph, the convergence of the axes would not affect the actual contour setting, although it might affect its precision. On balance, the best arrangement would seem to be either a slight permanent convergence of the axes, or some degree of adjustment to the convergence to suit the individual user. Under no circumstances should the axes be set with any permanent divergence, as this can lead to definite eyestrain. If a permanent convergence is provided the angle between the axes should probably not exceed 2°.

No question arises about parallelism of the axes of the eyepieces in the vertical plane, since the eyes have only a limited independence of movement in this plane. A deviation of ½° is the most that can be permitted and a more accurate alignment than this is desirable, except that some adjustment may be required to compensate for abnormalities of vertical muscle balance. This tolerance refers to the axes of the viewing system as a whole. The photographs themselves will have to be mounted more accurately than this relative to the targets, although even here advantage can be taken of an effect sometimes described erroneously but vividly as 'retinal slip.' The fusion process in the brain is evidently sufficiently fluid to overcome slight differences of alignment up to a few minutes of arc between different points in the two views, so that, provided there is sufficient fusion stimulus present in the form of obvious identity of the relevant parts of the two photographs, both target and photograph will be seen stereoscopically in spite of some differences of registration.

In addition to errors of registration in the vertical and horizontal planes, there may be an error of rotation about the axis of the system between the two pictures. Fusion can usually be maintained in spite of a rotation of even a few degrees, but this will depend on the subject of the photograph and will in any case give rise to considerable eye-strain. A rotation of more than 2° would be excessive, and a smaller tolerance than this is desirable.

One or two other points in the design of the viewing system deserve attention. Eyepieces of optical instruments are usually designed so that the exit-pupil is only a short distance (perhaps ¼ or ½ inch) beyond the last lens of the system. This means that a person with normal vision can bring his eye close to the eyepiece with his eyebrows lightly touching the eye-ring and with the exit-pupil of the eyepiece more or less in the same plane as his eye-pupil. Under these conditions he will see the complete field fully illuminated without any vignetting.

Persons who have to wear spectacles, however, are at a considerable disadvantage, since they cannot bring their eyes sufficiently close to the eye-piece to secure coincidence of exit-pupil and eye-pupil. As a consequence,

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the field of view is restricted and its boundary is diffuse instead of being seen sharply defined by the field stop. At least one firm, Messrs. Ross Ltd., has recently taken steps to meet this situation in the case of prism binoculars, since in their Spectaross binoculars special eyepieces have been designed incorporating a large-diameter eye lens, an exit-pupil located farther from the eye-lens, and adjustable eye-rings and a forehead rest to enable the binoculars to be used in comfort and with a complete field of view whether the user wears spectacles or not. This principle might well be extended to other optical instruments, and possibly to contour-plotting instruments, although where a person requiring a spectacle correction is to use a particular plotting machine over an extended period of time, a better solution would no doubt be to incorporate his correction in a lens attachment to the eyepiece.

Another fitting which is used in certain instruments designed for visual research is a mouthpiece mounting on to which the observer bites and by means of which his eyes can be centred and fixed relative to the exit-pupils of the instrument. An example of such an instrument is shown in Fig. XII (Wright, 1946). This device is especially desirable in photometric and colorimetric observations, since the visual efficiency of a beam of light is very much reduced if it is off-centre as it passes through the pupil of the eye and, therefore, is not incident normally on the retina. The image is also subject to

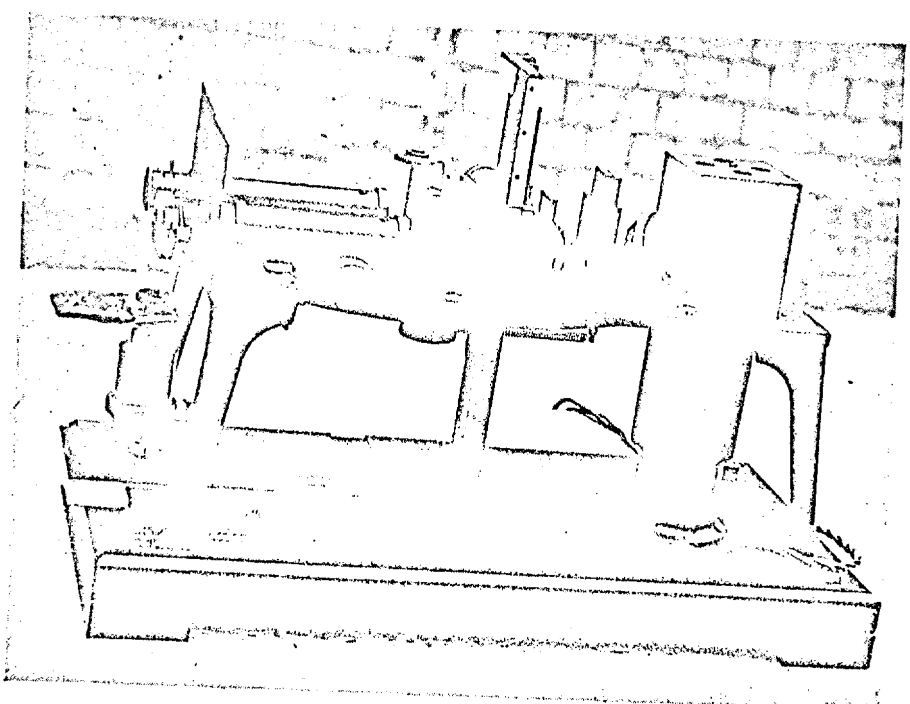

Fig. XII. A binocular-matching photometer incorporating a mouthpiece mounting to locate the observer relative to the exit-pupils of the instrument.

some unsymmetrical aberrations which might possibly affect the settings made in photogrammetry. A dental impression is less unpleasant to bite on than it sounds, and it might be worth while to test its merits in contour-plotting observations.

The functions of the field stop in a binocular eyepiece also deserve attention. The field stop and the image being viewed are normally in the same conjugate plane and both will be seen in sharp focus together. In theory the binocular images of the stop will be seen fused and will occupy a definite position in space, but the possible curvature of the horopter illustrated in Fig. VII suggests that the field stop may not appear in the same frontal plane as the target.

Now, in the case of stereo-prints, it has already been suggested that the bounding edge is important in providing a plane of reference for judging the contours, and the same may be true in an eyepiece system. On the other hand, it might prove a distraction and affect the setting of the target relative to the photograph. Again, when heights are being determined by changing the horizontal separation of the photographs, the observer has the convenient impression that it is the target that is approaching or receding, but if the target were a rather elaborate structure—if, for example, the field stop and the target were obviously associated together—the scene itself might appear to approach or recede. This would hardly be such a mentally satisfying conception or so conducive to accurate or rapid observations.

At least further thought might well be given to the field stop, and the advantages and disadvantages of a diffuse boundary to the field might be considered. Perhaps, also, tests with an illuminated surround might be worth while.

The Visual Task in Contour Plotting

The speed at which stereo-plotting machines can be operated is a tribute to the ability of the observer's eye and mind to assimilate complex information and emerge with a simple interpretation. This ability is acquired by training and experience and it is of great interest to analyse the nature of the visual task which the operator has to perform, provided the operator himself does not become too self-conscious of his visual processes. An analysis may have a direct bearing on the design of the apparatus and on the training programme, but if the observer were to think too much of what he was doing and how he was doing it, the results might be disastrous to his success as a contour plotter.

An adequate analysis of the task almost certainly requires a knowledge of the eye movements of the operator, but we can only infer these, since no direct records have been obtained during the act of contour plotting. We can assume that for a considerable fraction of the time, fixation is maintained on the stationary target yet, as shown in Fig. IV, this does not mean that the eye is absolutely steady; random movements of a few minutes of arc are certain to occur. In addition, there will be more conscious excursions to various nearby points of the stereo photographs in order to obtain as accurate an idea as possible of the three-dimensional structure of the scene in the immediate locality where the contour is being plotted. No doubt there will also be occasional excursions of the eyes to the more marginal parts of the field to secure a general idea of the contour trends. What is probably not known at all at the moment, is how far the sweeping of the photographs across the stationary fixation target may induce some degree of the 'pursuit' type of eye movement. If the target on which fixation was being maintained were the moving object then undoubtedly there would be some pursuit movements, although this would depend on the speed of traverse of the target.

Another question that arises is how far hunting occurs in contour plotting. The operator has to look slightly ahead of the point actually being plotted at any given moment and has to judge in which direction across the terrain the height is remaining the same. He cannot make the most accurate judgment of this until the target is alongside the new point and the chances are that there will be a slight error, which he can then correct. This will be repeated for the next point and so on, so that the contour line as plotted must consist of minute deviations from the true contour. It is a fascinating problem in what might be termed 'mental mechanics' to reduce this hunting to a minimum and to design the controls and the plotting mechanism so that their inertia matches the mental characteristics of the operator. One of the functions of the training of the operator must be to give him adequate confidence to plot the contours smoothly with the minimum of hunting and to adapt himself to match the equipment he is using.

One potential source of error, and a likely cause of differences of setting between one observer and another, is the influence which monocular clues, such as the effect of light and shade, the sharpness and contrast of the outline, the interpretation of perspective and so on may have on the judgment of the contour. The photographic quality of the picture, the optical magnification relative to the picture definition, the density of the photograph relative to the blackness of the target, are also attributes of the system that may affect the purely stereoscopic determination of the contour. For example, if the magnification is too great, so that the graininess of the emulsion is revealed, a marked flattening of the scene will be produced because the texture gradient of the grain will be zero; empty magnification may also make the picture more difficult to interpret.

Fatigue or poor health of the operator is known to influence the setting he makes, and the tendency is for him to dig the target into the ground when he is tired. Reduced precision of setting might well be expected under these conditions, but a consistent error in a given direction is less easy to explain. The most likely explanation appears to be that the binocular sense becomes less dominant, and monocular clues carry more weight; in particular, the sharpness, blackness and high contrast of the target may give the impression that it is nearer to the observer relative to the terrain than its disparity would imply. To offset this, the stereoscopic setting would then have to be in the opposite direction, that is, the target would be 'dug in' to the ground. Moreover, if each observer gives his own characteristic weighting to the monocular clues, this would account for any consistent difference or personal equation that might be found between one observer and another.

Auxiliary Observations in Photogrammetry

In addition to the actual observations made with photogrammetric equipment, binocular vision is, of course, used in the actual drawing of the maps, both in following the drawing point attached to the machines and in elaborating the maps on the drawing board. Close fine work of this quality can lead to eyestrain, and it may be worth while to refer to the use of prismatic spectacles that are recommended in certain industries where prolonged accommodation and convergence on near work are involved (Weston, 1949). The principle is simply to provide prism and lens power such that, for a given working distance, both the accommodation and convergence is relaxed as if the observer were viewing an object at infinity. These spectacles may be of quite high power for viewing objects only a few inches away, in which case they correspond somewhat to a binocular watchmaker's glass or they may be designed for working at ½ metre or 1 metre away. At least one manufacturer provides them in a convenient form made with the frames and lenses in plastic.

The drawing and study of contours lying very close together also involves the limited precision with which the visual axis can be defined, as discussed in Part I. If a row of dots or series of lines are placed so close together that they have an angular separation at the eye of the observer of less than about 3 or 4 minutes of arc, it is found that the observer can no longer maintain his fixation on any one of them, or identify or follow a particular line. If map drawing should involve this precision of working then eyestrain is almost certain to ensue and steps should be taken to provide optical magnification to relieve the task.

Chromatic Aberration and the Multiplex Process

In the Multiplex process the stereo pair of pictures are projected through red and blue-green filters, and the operator wears viewers with similar red and blue-green filters over the right and left eyes respectively. With the correct spectral transmission of the filters this arrangement ensures that each eye sees only one picture.

The fusion of differently coloured views to give three-dimensional relief is quite effective, although some persons find difficulty and even serious discomfort. A factor, however, which is often ignored is the chromatic aberration of the eye. The optical system of the eye is quite uncorrected so far as chromatic aberration is concerned and its decrease in power (expressed in dioptres) with increase in wavelength is illustrated in Fig. XIII. (Ivanoff, 1953.) Typical spectral transmission curves of the filters used in the Multiplex system are shown in Fig. XIV (Pestrecov, 1953) and the wavelengths

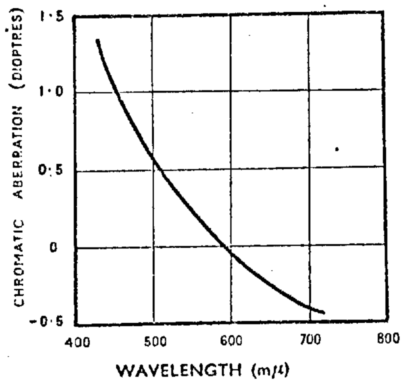

Fig. XIII. Chromatic aberration of the eye as shown by its decrease in power with increase in wavelength (after Ivanoff)

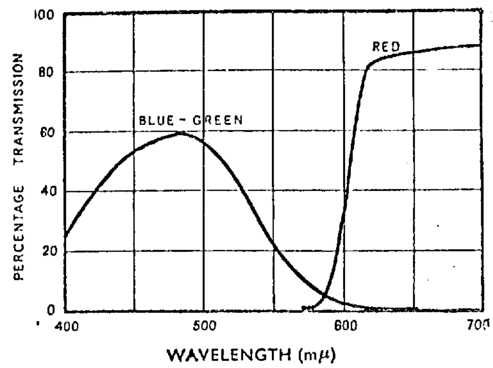

Fig. XIV. Special transmission curves of typical red and blue-green filters used in the Multiplex system (after Pestrecov).

0.48μ and 0.62μ can be taken as representative of the hues and average wavelength transmissions of the two filters. Fig. XIII then shows that there is a residual difference of power of about 0.75 dioptres between these wavelengths.

If this difference is not corrected, either by incorporating a negative lens with the blue filter or, as is to be preferred, a positive lens with the red filter, then two results will follow. In the first place, it will mean the exercise of differing amounts of accommodation in the two eyes if both views are to be seen sharply in focus; this is likely to be a potential source of eyestrain and of reduced precision of observation. Secondly, for persons about 45 years of age and over a significant loss of accommodation begins to be experienced and for many such people there will not be sufficient power for a sharp red image to be focused. This would prevent any accurate observations and even any effective three-dimensional reproduction of the scene.

It would be of interest to know whether tests have been made to compare colour defective observers and persons with normal colour vision in their ability to use the Multiplex equipment. Colour defectives will still, of course, be affected by the differing refractive power for the short and long-wavelength light, but they will be less troubled by colour differences when trying to fuse the two pictures. Probably the class of colour defective known as deuteranope (Physical Society, 1946) would prove most efficient at the observations, since they have poor red-green colour discrimination yet their light sensitivity to different wavelengths is similar to that of normal observers, hence the two pictures would have the same lightness as the normal.

Colour Stereoscopy

Finally, an effect should be mentioned which can give rise to an apparent difference in depth for differently coloured objects lying in the same plane. This phenomenon is due to a decentration of the eye pupils in conjunction with the chromatic aberration of the eye. (Duke Elder, 1932, p. 1067.) Fig.

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XV illustrates the paths of red and blue rays for the case of pupils decentred outwards, leading to a lateral displacement of the red and blue images on the retina. This displacement is in a direction corresponding to the disparity for the red object located in front of the blue, but for persons with pupils displaced inwards, the order will be reversed.

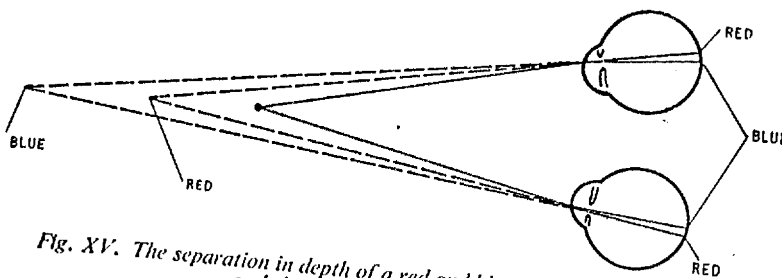

Fig. XV. The separation in depth of a red and blue object due to pupil decentration and the chromatic aberration of the eye.

This explains why roads marked in highly saturated colours on a map may appear to be slightly above or below the surface of the map. It might also have some effect on the correctness of Multiplex observations, but otherwise is unlikely to be of much practical importance unless colour photographs come to be used in aerial surveying. In that case, the centring of the exit-pupils of the plotting machine relative to the eye pupils of the observer might assume much greater importance and might make the addition of a mouth-piece mounting to fix the observer's head almost essential.

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DISCUSSION ON PAPER BY PROFESSOR WRIGHT

Dr. Miskin said he was most interested in the point regarding definition and made the statement that tiredness or lack of definition of the photograph would lead to a 'digging in' of the actual measuring mark. He asked whether Professor Wright had considered this fact in the relationship of the photographs themselves. If the photographs had soft spots, as happened with some present-day photographic equipment, would 'digging in' be likely to occur where there were soft spots and no 'digging' where the definition was good?

He was also interested in the convergence factors which had so adequately been put forward and he thought the point was well-illustrated. He remarked that when Professor Wright had visited him he noticed that the Professor used a prism to obtain some degree of convergence when viewing through the instrument.

Another important point was in connection with the anaglyphic method of viewing as he believed there was some delay in reception in the brain of red and green light, and he wondered what effect that slight time lag might have in the perception of the three-dimensional model.

The interesting part, so far as the photogrammetrist was concerned, was the ability to stop fatigue, and he asked Professor Wright if he had any actual figures for fatigue values comparing monochromatic lighting and anaglyph lighting.

Professor Wright answering the first point of Dr. Miskin's question said he thought that with soft spots there might be a tendency to 'dig in'. He understood the question of photographic quality of the pictures might be made a subject for international study and standardisation.

Regarding the time lag with red and green pictures, Professor Wright said that this could cause the pictures to appear to jump about, although he had never observed the effect. There was also a certain amount of rivalry in the two colours which caused difficulty in fusing.

He said he had no figures regarding fatigue, because he was not really working close enough to the problem, but fatigue was a difficult thing to measure.

Mr. Fish asked Professor Wright whether he had any information regarding the phenomena which some people found when viewing stereoscopically, that the resultant picture had better definition than either of the two single pictures. He wondered whether it was because the pictures, at the scale viewed, tended to show the grain. It was a fact that quite a lot of the area of the picture looked at must have differences in definition between the two eyes, because the 40 per cent overlap was in the outer part of one and the centre of the other photograph.

He said that use had been made on occasions of stereoscopic photographs taken from forward looking obliques, which depended on the forward motion of the aircraft for stereoscopic effect, and these had produced some queer results.

He pointed out that in many instances there must be differences in scale between two pictures, but the eye still appeared to give stereoscopic vision and he wondered whether this had ever been investigated. Another thing arose under the same conditions, on occasions the angle of convergence was very great and Mr. Fish asked Professor Wright whether he could give any idea what the limiting angle was for a pair of eyes to see stereoscopically.

Regarding the photographs of the saccadic jumps in the movement of the eyes, he asked whether there was any relationship between the two eyes or if they were random between the two.

Professor Wright agreed that better definition was obtained with two photographs, and must in part be due to the averaging out of the grain effect.

Professor Thompson asked whether there was a similar improvement when a natural object was examined with two eyes.

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Professor Wright said our visual acuity when looking at perfectly defined objects was better with two eyes than with one, no doubt because the limitations of the retinal mosaic and retinal response were also to some extent averaged out.

Mr. Fish remarked that it did appear when looking at two poor pictures you got one better one out of them.

Professor Wright referred to his slide showing dot patterns and said his point in showing that was to emphasise that in photography where there was grain, if there was too much magnification so that the grain became apparent, it tended to produce a flattening effect of the picture.

Regarding the difference in scale, Professor Wright said that similar trouble was experienced with people who had one eye giving a different size image on the retina from the other. This subject had been studied in America and he knew of experiments by Lord Charnwood in this country.

The limit of convergence depended on age and focusing power. It was possible to get a three-dimensional effect where the subject was converging to a distance of 10 inches, or nearer.

Mr. Fish said he was thinking in terms of the fact that the object was being viewed from widely divergent positions.

Professor Wright said it was a question of how much disparity one could stand and still fuse.

Regarding the saccadic movements, the eyes did go in harmony to within close limits. The recent work carried out by Dr. Mary Lord on binocular movement records confirmed this. He said that with photographs taken from widely separated points, the views might be so different that fusion was very difficult or impossible, but as this would depend on the scene being photographed, it would not be easy to give a value to the limiting angle. Angular disparities of several degrees could be overcome by change of convergence, but if the disparity varied too drastically from point to point of the photographs, the three-dimensional effect that could be observed would be very poor.

Mr. Dawe said he had one or two things to comment on. Firstly, the question of whether an operator was actually 'hunting' when searching for contours. He thought he was, but the more practised and experienced the operator the less 'hunting' was done. The particular set-up in the instrument (that is the positions of the pictures relative to the two separate reference marks in the binocular instruments) indicated the correct plane. A quick check could often be made by closing each eye alternately very quickly. If the mark appeared to jump it indicated that the mark was in the wrong plane whereas when the correct position was occupied there was no apparent movement. The actual process of plotting the contours must inevitably entail a certain amount of 'hunting' and feeling when the dot was about to split into the ground or come 'off the deck.'

No planned study of fatigue had been made, but operators on anaglyph work asked for a change more often than those on the binocular instruments. If necessary convergence down the telescope of an A5 or A6 could be engineered to a certain extent on the present models by the small adjustment of one of the prisms without affecting the internal set-up of the optics.

Professor Thompson referred to the viewing of repeated patterns by over-convergence of the eyes. The fused patterns then appeared considerably closer to the observer than the original object. Although it was said that this was due to the convergence it was unquestionably due partly to the presence of other objects in the field of view which, although they appeared double, gave a reference plane in depth.

Professor Wright said he had given demonstrations recently to show that some appearance of depth could be observed even when an object was seen double, but this had, of course, been known for a long time.

Mr. Cook referred to the request for convergence in the binocular machine and asked if Professor Wright thought it was more of a mental request than optical necessity for the eyes to converge on a point required when looking into the binocular attachments.

Professor Wright said it was difficult to separate the two, the eye and the mind. It was difficult to dissociate what you saw and associated with past experience and maybe what your muscles and lenses were demanding. He would not like to distinguish between the two.

Mr. Richards said that regarding convergence it appeared that the eyes were more content or rested if they were fixed on some distant point. In a binocular instrument was it not an advantage if such instruments were non-converging so that no strain or undue work was given to the eyes of an operator when the sight was kept near parallel.

Professor Wright agreed that this was a reasonable argument, but if the act of looking through a binocular eyepiece produced a natural tendency to converge, the best solution might be to have a very slight convergence. It might at least be helpful to some people and for most beginners if the convergence could be adjustable.

Mr. Richards wondered whether this would have any bearing on the fact that after an operator had worked for a while he tended to 'dig' on the model because the eyes wanted to converge but they were being forced apart to look at the floating mark and in doing so, when looking at the model later on in the day, it would appear that the reading was lower on that point, and it would seem that the eyes were being forced outwards.

Professor Wright said he had been trying to think out an explanation for this 'digging in' but he did not see how it was going to work on that explanation. Whatever applied to the dot would apply to the photograph, so there would be no residual disparity. His suggestion of the effect of the sharpness of the dot relative to the less sharp photograph seemed to provide a more plausible explanation, but he had no proof of it.

Mr. Attwell mentioned the difficulty initially in fusing the floating mark due to the indefinite nature of the mark. Disregarding the possible objections that the experienced operator might have, he asked whether Professor Wright thought if the floating mark was more definite than a dot, such as a split cross, fusing in the initial stages of training would be easier.

Professor Wright thought this was very likely and said that if there was a bit more structure to the object one was trying to fuse it would be done more readily. He imagined that in the end the dot virtually acquired a personality and was not just a dot, but something one looked forward to looking at, but until that stage was reached a more complicated pattern would provide a stronger stimulus to fusion.

Colonel Gardiner asked about the effects of colour. With coloured photographs would the marks 'dig in' more in some portions of the photograph than others? Was colour photography going to be a nuisance and black and white the best thing?

Professor Wright said he did not know and he had not yet carried out any experiments with colour photographs. He thought there would be a gain from less graininess in the picture with coloured photographs. Colour would also probably help because it would add to the reality of the situation.

Colonel Gardiner asked what would be the effects of the different colours. Professor Wright said there would not be the anaglyph trouble of the two eyes seeing different colours. Errors due to the 'colour stereoscopy' effect described in the paper might, however, be important unless the exit pupils of the instrument were accurately located on the visual axes of the observer's eyes. This might make the use of a mouthpiece mounting essential.

Professor Thompson said that more work could be done on the tolerances permissible in the direction perpendicular to the eye base. For purposes of correspondence setting it was not sufficient, he thought, that the photographs could merely be fused.

Professor Wright agreed that the tolerances he had suggested for fusion of the pictures would be much too large as tolerances for the location of the photographs in a plotting machine.

Professor Thompson thought it had been a most interesting paper. Photogrammetrists were the principal users of stereoscopy in a serious way and there was clearly a need to enlist the support of men such as Professor Wright who had studied the physiology of the subject. He hoped that this paper would lead to further collaboration. Professor Thompson concluded by thanking Professor Wright on behalf of the members of the Photogrammetric Society for having taken so much trouble in preparing and delivering such an interesting paper.