HETEROPHORIA BY A COMPUTER-CONTROLLED PHOROMETER

LATERAL HETEROPHORIA
AND ITS SEQUENTIAL MEASUREMENT BY A
COMPUTER-CONTROLLED PHOROMETER

by

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ABSTRACT

This study is concerned with the repeated measurement of lateral heterophoria over a time interval of up to 3 minutes. Such measurements were made possible by the use of a computer-controlled phorometer which was devised especially for this project. This phorometer was programmed to simulate a number of different phoria tests. The results obtained from these tests indicate that the commonly used methods of dissociation are not as free from fusional interference as had been supposed.

Two new phoria tests are introduced. One is an automated version of the cover test and the other, the fused-images method, is original to this study.

Results of clinical interest are presented. Those regarding strabismus are particularly interesting.

Heterophoria is given a new definition and a new phoria test is proposed.

RESUME

Ce travail porte sur la mesure répetée des hétérophories latérales pendant des périodes de 3 minutes. Ces mesures ont été faites au moyen d'un phoromètre contrôlé par un ordinateur. Ce phoromètre avait été programmé en vue de simuler différents tests de phorie. Les résultats obtenus à partir de ces tests indiquent que les méthodes de dissociation habituellement utilisées ne sont pas aussi libre d'interférence fusionnelle qu'on ne l'avait supposé.

Deux nouveaux tests de phories ont été suggérés. Un de ces tests est une version automatisée du "cover test" et l'autre, soit celui de la méthode des images fusionnées, est unique à cette recherche.

Des résultats d'intérêt clinique sont apparus, surtout dans les applications au strabisme.

Une nouvelle définition des hétérophories est présentée ainsi qu'un nouveau test pour les mesurer.

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CHAPTER I

INTRODUCTION

The term lateral heterophoria describes the vergence change which occurs when a person's power of binocular fusion is artificially inhibited. When fusion is rendered impossible, the relative angular position of the eyes alters and the amount of this change is called the heterophoria. When the angular change is measured in the horizontal plane, with the head in the erect position, it is called the lateral heterophoria.

When binocular vision is normal the eyes are automatically positioned so that the images on the retinae will be appropriately located for use by the visual cortex. The cortex analyses the image pattern and, among other things, creates the perception of depth. It also gives the spatial localization of objects without any noticeable diplopia. The cortical mechanism which works to maintain single binocular vision is called fusional compulsion. If for any reason the fusion is disrupted, objects will appear doubled. When fusion is rendered inoperative by an artificial means the eyes are said to be dissociated.

In order for single binocular vision to occur, it is necessary that the eye's position be controlled with great precision. The visual system has within it a sub-system called the vergence system. This system is responsible for the binocular fixation of the object being regarded. The term vergence refers to the included angle between the visual axes. Convergence indicates a relative increase in vergence and divergence indicates a relative decrease.

If an object is fixed binocularly the total positional error of the two visual axes must remain within about 10 min of arc otherwise diplopia will occur. The angular error that can be tolerated without the onset of diplopia differs from person to person. It also depends on the part of the visual field in which the object is located. During single binocular vision, errors of fixation are not perceived and it is only by some artificial means that these disparities of fixation can be noted.

For heterophoria to occur, the compulsion for fusion must be suppressed. A number of methods have been used for this purpose; all of which rely on the use of a special device. Since all dissociating devices must work so as to defeat single binocular vision, it is obvious that heterophoria is an artificially produced condition.

The measurement of lateral heterophoria is complicated by the variety of dissociating devices that can be used. Over the last 100 years a number of means of dissociation have been used. Of these only three enjoy general use today. These are:

1. An ophthalmic prism placed before one eye with the prism's base-apex line parallel to the median plane of the subject's head.

2. The Maddox-rod placed before one eye with the axes of the cylindrical lenses in the horizontal plane.

3. The cover test, in which one eye is alternately covered and uncovered by an opaque screen.

The ophthalmic prism produces true diplopia without any appreciable distortion of the images seen. The Maddox-rod does not produce diplopia in the normal sense but instead it distorts the images seen by one eye to such an extent that fusion is considered to be impossible. The cover test makes fusion inoperative because one eye is looking at a blank screen. Diplopia does not occur in the cover test except when the eye is uncovered briefly. Uncovering is necessary so that the change in eye position can be determined.

The deviation of the non-fixating eye is usually measured by means of optical cancellation. When this eye adopts its heterophoria position, the images seen by it appear to be displaced with respect to those seen by the fixating eye. The amount of this displacement can be determined by using a variable prism whose prism power can be used to displace the images seen through it. The prism power necessary to restore the images to their position of zero heterophoria is the amount of the subject's heterophoria. In the case of lateral heterophoria, the prism's base-apex line is placed horizontally and the power is adjusted until the reference images are seen to be in vertical alignment. The prism's power, in prism diopters (Δ), is normally used to quantify this change in vergence.

It is also possible to measure the heterophoria objectively by means of an electronic eye movement monitor.[19] This is a procedure that has been neglected but its potential for phorometry is great because with it the phoria can be measured continuously.

The numerical value of the heterophoria depends, to some extent, on the distance between the object regarded and the observer. A distant object requires little vergence and accommodation whereas a near one requires a large vergence for fusion and considerable accommodation for clear vision. The synergy between accommodation and convergence always enters into play so that even when dissociated, the eyes increase their vergence when the accommodation is increased.[9] It is for this reason that the refractive state of the eyes must be corrected before heterophoria measurements are made, otherwise misleading results are obtained.[4]

Phoria measurements have been an integral part of ophthalmology and refraction for many years. This was so because heterophoria was thought to indicate a preferred vergence for a given object distance. If the heterophoria were not zero it was felt that fusional compulsion had to work against the phoria in order to provide binocular fusion. This idea was never properly expressed but it was implied that additional oculomotor work was required to move the eyes from the dissociated to the fused vergence. It was felt that this additional work constituted an unnecessary load on the neuromuscular components of the eye and was therefore undesirable. Symptoms of ocular discomfort or fatigue were attributable to heterophoria, according to this theory, and in some cases surgery was performed on the extraocular muscles to reduce or eliminate the phoria.[27] In other cases additional prism or dioptric power was added to the patient's ophthalmic prescription.[18]

Although the cause of lateral heterophoria is still unknown, it was thought by some to be an indication of latent strabismus.[24] Others suggested that anatomical peculiarities in the orbit, muscles or ligaments were contributing factors.[10] Little interest is shown in lateral heterophoria at the present time with the exception of the work of R. A. Crone. His recent publications show the old explanations of heterophoria to be inadequate and he has proposed a theory of his own.[8] This theory suggests that lateral heterophoria is due to a drive for image disparity which has been perverted due to a lack of fusible images.[7]

Although heterophoria had been measured routinely for over 100 years its dynamic characteristics had never been determined. It was known from simple observation that the heterophoria could have short term changes in value but the amount and time course of these changes was never studied. If phoria measurements were repeated during an examination it was, as a rule, to check on the quality of the initial measurement. Studies in which phoria measurements were repeated after many years showed the phoria to be essentially unchanged by the passage of time.[38]

The object of the present study was to record the short term variations in lateral heterophoria and to determine its time course following the dissociation of the eyes. In order for this to be done the phoria had to be repeatedly measured with the elapsed time between measurements kept as short as possible. No existing phorometer was capable of this performance because they were all controlled manually. Since automatic control was a pre-requisite for effective operation, a computer-controlled phorometer was devised.

A motorized rotary prism, called a stepping prism, had already been developed by me so this was used as the key element in the new phorometer.[20] This prism was used to determine the amount of the phoria, by optical cancellation, in the manner already mentioned. A PDP-8 digital computer was interfaced with the stepping prism so that the prism's power was under programmed control at all times. Computer-control was indispensable because of the high operating speed required of the phorometer. Various dissociating methods were used in conjunction with the stepping prism. In general the computer-controlled phorometer met the requirements of this study.

5.1

It should be born in mind that all previous phoria measurements had been made by hand using a Risley rotary prism.[33] Although simple to use, this prism requires considerable manual dexterity if its power is to be changed smoothly. It also suffers from a nonlinear relationship between the rotation of the input shaft and the prism power that this produces. A further limitation on the prism's performance is that the power scale, marked on the prism unit, is graduated in steps of 2Δ. Because of this, the phoria is often recorded to the nearest diopter and at best is estimated to half a diopter.

If one compares the performance of the same prism under computer-control with its manually operated counterpart the former is obviously superior. By its nature the stepping prism cannot change its power continuously. Instead it changes power in small increments. These changes are produced by means of a stepping motor which is connected to the prism's input shaft. Since the rate of stepping is under the control of the program running in the computer, any nonlinearities in the system can be eliminated through programming. The resolution of this stepping prism was ± 0.1Δ. The prism was calibrated by means of the displacement it produced on a laser beam passed through it. The maximum rate at which the prism's power could be altered was 0.1Δ/msec. Because of these features, the phoria measurements made with the computer-controlled phorometer were close to the ultimate in precision for subjective phorometry.

Over 160 phoria tests were made using the computer-controlled phorometer. Most of these lasted for 2 minutes and 55 seconds. The number of phoria values recorded during a test depended on the method being used but the maximum was in the order of 175. A typical prism-diplopia recording would require about 70 responses during the test period. At this rate, the total number of individual phoria measurements must have exceeded 11,200.

The results obtained from the tests were important for a number of reasons. These were:

1. These were the first subjective phoria measurements to be made in rapid succession.

2. The duration of the test, about three minutes, was long enough to show the variability inherent in the phoria.

3. Different dissociating methods were compared under otherwise identical test conditions.

4. New information was obtained on the behaviour of the human vergence system under dissociated conditions.

Although the results of this study are valuable they are also disconcerting because many of the conventional ideas concerning heterophoria are placed in jeopardy. This is particularly true regarding dissociation and the choice of the dissociating device.

CHAPTER II

LATERAL HETEROPHORIA AND ITS MEASUREMENT

I. FIXATION DISPARITY

It has been pointed out that there is more often than not an angular disparity between objects seen with one eye and those seen with the other. Since objects regarded directly must have an image which falls directly at the centre of the foveae, this angular disparity is usually thought of as being relative to the object being fixed. Any two images of the same object, one on each retina, which have the same angular position relative to the foveae are said to fall on corresponding points.[28] Since there will be no angular disparity between these images they will be as unique as those which fall directly on the foveae. The spatial localization of all possible object positions which will result in zero disparity between the images is called the horopter. The horopter of Vieth-Müller is a geometrical construction used to determine the position of all objects having zero disparity.[28] This horopter is a circle which passes through the object fixed and the anterior nodal point of each eye. The construction of the Vieth-Müller horopter is illustrated in Figure 1. In part A of the figure two horopters are shown, one passing through point P and the other through point 4. The points labelled 6 and 7 will not give rise to any disparity in their image positions relative to the foveae because they lie on the horopter. This correspondence between the points is expressed schematically in part B of the figure. The presentation follows that suggested by Ronne.[34] The rows of points are considered as cortical representations of the corresponding points for one retinal meridian which passes through the central fovea. The fovea is

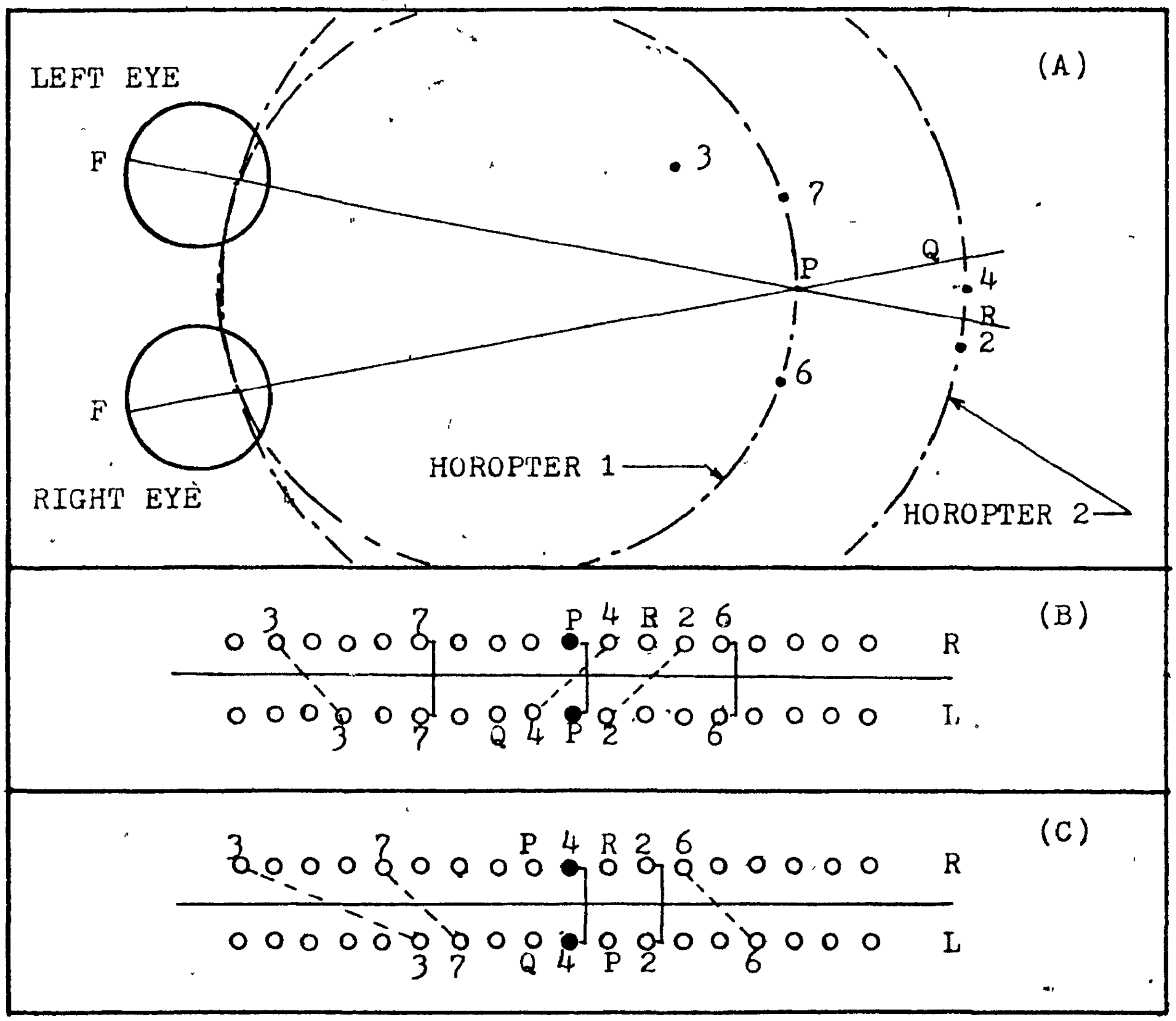

Figure 1. A schematic representation of a subject regarding objects located in a horizontal plane. See the text for details.

indicated by the black dot. The meridian for the right eye is marked R and that for the left L. Perfect fixation of P is shown when P falls on both black dots. The solid line joining the images is intended to indicate that there is no disparity between them.

One might suppose that when an object, such as P, were regarded directly the correspondence between the images would be as shown in B of Figure 1. This is often not the case because it is possible for someone to think that he is fixating a particular point when in fact his eyes are not perfectly directed at it. The reason that such a fixation disparity is not normally evident is that there is a certain range of disparities which will never result in diplopia. Objects which fall within this range are always seen as single and the name given to this zone of single binocular vision is Panum's fusional area.[28] Thus if, as is shown in Figure 1 part C, point 4 were regarded directly and points 6 and 7 were within Panum's area, they would be seen without diplopia. If point 3 lay outside Panum's area it would be seen double. If one were to regard 4 but with a fixation disparity such that the visual axes crossed at P, the general impression would be the same as long as 4 remained within Panum's area. The extent of this area varies between individuals and also between central and peripheral vision. Disparities which occur within the central visual field can amount to 10 min of arc without causing diplopia. Peripheral disparities can amount to 40 min of arc before diplopia is noticed.

A fixation disparity can only be made manifest by special techniques.[30] These invariably make use of polarized light. The subject looks at a target which is seen normally by both eyes. This target stimulates binocular vision in all respects except for the presence of two lines of polarized light. One of these lines is seen by the right eye and the other by the left. Any fixation disparity which exists will be exposed by the alignment of these two lines. Often the lines are adjustable and the subject moves them into apparent alignment while wearing polarizing glasses. Any error in this alignment is said to be due to a disparity of fixation. The amount of this disparity is usually expressed in minutes of arc.

The amount of the fixation disparity depends on the vergence of the eyes and on the state of accommodation. Thus the disparity for distance vision may differ from that for near vision. In addition, it is found that the amount of disparity alters if a change in vergence is forced by means of prisms. A forced change in accommodation, through the addition of ophthalmic lenses, also changes the fixation disparity. Some of Ogle's results for such forced changes are shown in Figure 2.[30] It should be noted that an enormous change in vergence is required to produce a small change in the disparity. In a sense, the vergence system may be said to prefer the disparity because it appears to make every effort to retain it. This is also true for forced changes in accommodation as is shown in graphs A-2 and B-2 of Figure 2. The other graphs in the figure show how the disparity changes with a change in forced vergence. The forced vergence necessary to abolish the disparity is called "the associated horizontal phoria". This name appears to have been coined by Ogle.[28] It is unfortunate that "phoria" appears in this name because this has nothing to do with heterophoria as it is normally understood.

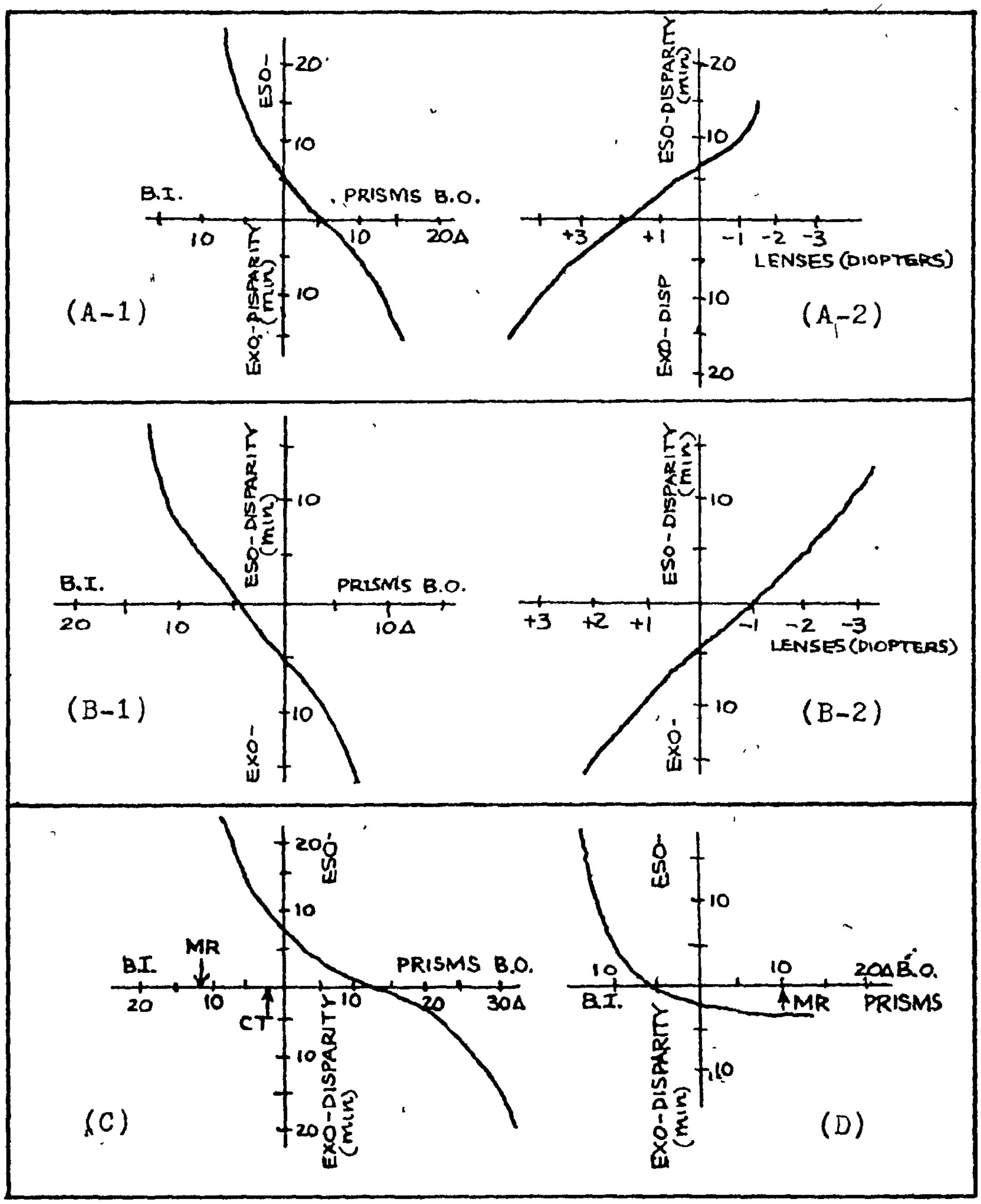

Figure 2. Typical fixation disparity results taken from Ogle.[30] Near test distance (33 cm). Changes in the disparity with different amounts of forced vergence are shown in A-1, B-1, C and D for 4 different subjects. Changes in the disparity with forced accommodation changes are shown in A-2 and B-2 for the same subjects as A-1 and B-1 respectively.

II. DISSOCIATION

Under normal circumstances binocular vision resists diplopia. If one wished, for some special reason, to disrupt the normal reflex for fusion it would be necessary to use some special dissociating device. Dissociating devices are particularly important to the study of lateral heterophoria because the whole concept is based on their use.

Perhaps the most obvious means for producing dissociation is to simply block the vision of one eye by means of a screen. The images seen by that eye will not only be different from those seen by the other but they will also be out of focus because of the proximity of the screen. When one eye is covered in this way the other eye is used for fixation. This means of dissociation has a serious fault in that the stimulus for accommodation is different for each eye when the cover is in place. When the cover is removed and replaced an accommodative change may take place in the occluded eye.

The human eye can only sustain a limited demand for a vergence change in the vertical direction. If a prism with its base in the vertical direction is placed before one eye, diplopia will result if the prism power exceeds about 3Δ (1.7 deg). It is common practice to use a 6Δ prism as a means for producing dissociation. With this device the accommodation of both eyes can remain as it was before dissociation.

The Maddox-rod is an ingenious dissociating device consisting of an array of cylindrical lenses placed before one eye. In order for the Maddox-rod to function, a small bright object must be regarded.[26] The image of the object is distorted by the cylindrical lenses and the object appears to be a bright vertical line. Sometimes the lenses are tinted red as a means of further inducing dissociation. Dissociation results because the free eye sees a different scene to that seen by the eye looking through the Maddox-rod. Accommodation is not well controlled because the power of the cylindrical lens system varies from zero along the axis of the cylinder to a large value at 90 deg to the axis. If the Maddox-rod is tinted red, matters are complicated by the chromatic aberration of the eye.

The polarization of light offers a convenient means for dissociation but it has not been applied to phorometry. If the subject wears polarized lenses, such as are used for viewing stereoscopic pictures, the images seen by one eye can be made different from those seen by the other. In essence, two pictures are projected on a screen with the light from one picture polarized at 90 deg with respect to the light from the other. In order for complete dissociation to occur, the field of view of the subject must exclude all sources of unpolarized light.

III. LATERAL HETEROPHORIA

As far as can be determined, von Graefe (1867) was the first to develop a method for disrupting the fusion of the eyes and to measure the position adopted by them under this condition.[42] The system of names used to describe the dissociated position relative to the fused condition, is due to George Stevens (1887).[39] A complete description of the terms used is given by Duke-Elder in his Text-book of Ophthalmology.[15] Of interest in the present study are the words orthophoria (to bear straight), heterophoria (other bearing), esophoria (bearing inwards) and exophoria (bearing outwards). The word cyclophoria was introduced by Savage in 1891 to describe a torsional phoria.[35]

As defined by Duke-Elder, orthophoria is said to be the ideal condition wherein the oculomotor apparatus is in perfect equilibrium so that both eyes retain their normal positional relationship (that is, remain directed upon the fixation point) even when their activity is dissociated by the withdrawal of the controlling influence of fusion. This ideal equilibrium is, however, not common for distant objects and non-existent for near.[15]

It is also said that normally both eyes are maintained on the fixation point only under stress with the aid of corrective fusion reflexes. If fusion is made impossible by dissociation, one eye deviates and this condition is termed heterophoria or latent strabismus.[15]

The preceding definition of heterophoria is the conventional one. In it orthophoria is implied to be the ideal state and heterophoria to be a departure from the ideal. The statement that orthophoria is not a condition commonly found shows the definition to be inadequate.

In 1928 Ames and Glidden compared lateral heterophoria values with those found for, what was later to be called, fixation disparity.[2] The discovery of fixation disparity and its correct interpretation was due to Lau.[23] The possibility of a link between heterophoria and fixation disparity was considered by Ogle and recently Crone has advanced the theory that fixation disparity is the cause of lateral heterophoria.[8]

Aside from the work of Crone there seems to be little interest in heterophoria at the present time. The old idea of muscle imbalance still holds sway, as was indicated by Snydacker when he wrote that "the value of the Maddox-rod as an instrument for measuring muscle imbalance has been amply demonstrated by widespread clinical use."[38]

One fairly recent development in the orthodox interpretation of heterophoria is the study of variations in the phoria with elevation and depression of the gaze. It is suggested that there is a connection between this and the A and V syndromes of lateral heterotropia.[41]

The reason why heterophoria occupies such an important place in ophthalmology was expressed concisely by Duke-Elder when he said that, "there is . . . no fundamental distinction between latent and manifest squint; the difference is qualitative, lying partly in the degree of dissociation, but essentially in the effectiveness of the patient's efforts to compensate for it by fusional reflexes. . . . In terms of strabismus, heterophoria is a latent squint made manifest by the suspension of fusion."[15]

The notion that lateral heterophoria is a latent squint made manifest through the suppression of fusion has given it the reputation of being something that had to be overcome before single binocular vision was possible. The effort of continuously overcoming the phoria has been singled out as a cause of asthenopia and eye-strain.[18] Because of its association with strabismus, heterophoria has been treated by orthoptic methods as well as by surgery.[25]

It has been suggested that heterophoria causes a decrease in the ability to perceive depth through stereopsis. Vision tests for pilots include measurements for heterophoria and if certain values are exceeded the candidate will be disqualified.[44] This restriction may be quite unjustified because some claim that there is little relationship between lateral heterophoria and stereopsis.[3]

It has been suggested that certain cases of heterophoria are caused by certain anatomical conditions.[10] While this may be true, anatomical abnormalities need not lead to heterophoria. Crone cites a case in which one eye was displaced by 13 mm over a period of 40 years.[7] During this change of position, eye movements were unimpaired and orthophoria was retained.

Because of the synergy between accommodation and convergence, the measurement of heterophoria is commonly performed during the refraction of the eyes.[4,18] The ratio of accommodative convergence to accommodation (AC/A) is often determined by changing the accommodation required for a given object distance and measuring the resulting change in phoria.[9,29]

Not everyone agrees with the traditional views on heterophoria. Abraham suggests that, "the older concept, still retained by faulty definitions, which suggests a direct relation to the position of rest is outmoded and only confusion can result therefrom."[1] He takes the view of Dobson that heterophoria, as measured by the usual tests, gives evidence as to the state of activity of the convergence function under test conditions.[12] In contradiction to the view held by some, Abraham says, "No real evidence exists to support the opinion that phorias determine the type of strabismus which may occur."

Crone has made the greatest break with tradition. In his article on micro-anomalous correspondence and its role in heterophoria he states five "facts" which he considers to be a challenge to the usual explanation of heterophoria. These facts are summarized as follows:[7]

1. Major anatomical abnormalities are frequently accompanied by orthophoria.

2. Orthophoric subjects to whom prismatic lenses are applied are found to be orthophoric again after a period of adaptation with such lenses.

3. In the majority of cases of severe heterophoria, no evident anatomical cause exists for an abnormal position of rest.

4. Where corrective prisms are prescribed in cases of heterophoria, it will often be found that the condition, as measured through the lenses, returns after a time.

5. . . . prismatic or surgical correction frequently leads to failure.

Crone's study on motor fusion at constant disparity led him to note that, "the conception of the motor function of fixation disparity points to an intimate connection between fixation disparity and the fusional tonus of heterophoria . . . in which the disparity might even be the primary cause of the heterophoria."[6]

IV. METHODS FOR DETERMINING THE PHORIA

The methods of phoria measurement discussed in this section are limited to those dealing with lateral heterophoria. In some cases the same methods are used for measuring the vertical phoria. A more complete listing is given by Cridland.[5]

Von Graefe's prism-diplopia test. The prism-diplopia method of von Graefe is based on the dissociating effect of a prism placed, base vertical, before one eye.[4] The ensuing vergence change is usually measured with a Risley rotary prism.

As recommended by Savage, the dissociating prism should be placed before the same eye as the rotary prism.[36] He also stated that, "the principle on which all the tests possible to a phorometer rest, is that the image in one eye, throughout every test, shall be undisturbed; that the head shall be erect; and that both eyes and the object . . . shall be on the extended horizontal plane of the head." Savage's description of the test is worthy of quotation because it is one of the most explicit;[36]

> With the instrument properly levelled before the right eye, the axis of the rotary prism vertical, and the 6 diopter prism base up, in the slot toward the face, the false object is made to appear below the true, and if directly under it, there is lateral orthophoria. The rotary prism turned in either direction will make the false object go either to the right or to the left of the vertical line through the true object, which must be, at all times, the one looked at. Should the false object not be under the true, turning the rotary prism in the proper direction will place it there. The test for lateral orthophoria, in the near, is made by holding a card with a dot or cross in its centre, at the reading distance.

The power of the dissociating prism is considered adequate if it exceeds the subject's ability to maintain fusion. The dissociating power used by von Graefe, according to Maddox, was 3.5Δ for distant vision, while for near a power of 8Δ was used.[26] Savage suggested the use of a 6Δ prism and Scobee and Green used 5Δ during their study.[36,37] Appendix A shows the conversion between prism diopters and degrees of deviation.

In spite of criticism against it, the prism-diplopia test is frequently used. Scobee and Green, in 1947, concluded that it had a high correlation with the test that they considered to be the best, the screen and parallax test.[37]

The cover tests. Tests for lateral heterophoria based on the covering and uncovering of one or both eyes alternately are considered by most to be the standard by which other methods should be judged.[13,14] Scobee and Green stated that, "of all heterophoria tests, the screen and parallax test eliminates a greater number of innervational factors than any other test and thus allows the closest approach to the position of absolute rest."[37] The screen and parallax version of the cover test is the preferred one and sometimes it is performed with a Maddox-rod before one eye. Scobee and Green's description of the screen and parallax test is as follows:

> A 1 cm light was used at 20 feet and an ophthalmoscope with the head removed was used at 13 inches. A cover was shifted from one eye to the other; square prisms being changed behind the cover until any objective movement of the eye and any subjective movement of the light had ceased.

With the addition of a Maddox-rod, Dolman created the Maddox-rod screen test.[13] Scobee and Green's version of this, called the screen-Maddox rod test, is described as follows:[37]

> At 20 feet, the test object was a muscle light 1 cm in diameter; at 13 inches, it was an ophthalmoscope with the head removed. All lights in the immediate vicinity of the muscle light were turned out but the room was not entirely darkened. With the Maddox rod placed before the non-dominant eye, a cover is also held before the same eye and removed regularly for a period of 1 second at about 3 second intervals, meanwhile allowing the dominant eye to maintain fixation constantly. This very brief uncovering or "flashing" of the non-dominant eye has for its purpose a further weakening of the fusion control. For the measurement of heterophoria, a Risley rotary prism is rotated into position (also before the non-dominant eye) and set between 3 and 4 diopters "off" of the zero position; this forces the examinee to make some adjustment even though orthophoria is present. The examinee grasps the handle of the rotary prism and, while the muscle light is being "flashed" before the eye behind the Maddox rod, he is instructed to adjust the line so that it bisects the light.

Cover tests are considered to be "delicate" in that skill is required of both examiner and subject. When the cover test is performed objectively by adjusting the prism until the eye no longer moves when covered and uncovered, the phoria can usually be measured to within 2 deg. Lancaster claimed that, "with a good light, a loupe and a good patient it was possible to measure 2Δ (1.2 deg)."[18]

The Maddox-rod. The most popular means of determining the phoria is the Maddox-rod test. It is similar to the prism-diplopia test except that dissociation is produced by the use of the Maddox-rod. Maddox's original rod was a short length of glass rod, about 4 mm in diameter, but current practice is to use a system similar to a number of rods stacked together with the axes of the rods lying in the same plane and the rods in contact with each other.[26] Each rod is a cylindrical lens with great dioptric power in the meridian at right angles to the axis and zero power in the meridian parallel to the axis. When an object such as a flame or a small lamp is regarded through the Maddox-rod, its width in the axial meridian is unchanged but its width in the direction at right angles to the axis becomes very large to the effect that the light source is drawn out into a line of light. Regarding the use of the Maddox-rod test Duke-Elder said that:[15]

> The Maddox-rod is the most widely used, the most simple and accurate of all tests for small deviations and high testimony has rightly been paid to its value. It cannot, however, be said to be perfect since there is undoubtedly some tendency to attain fusion even although the images are so dissimilar, and a tendency to convergence may introduce a bias towards esophoria. If, however, it is used in combination with the cover test, these difficulties are removed and the combined test becomes one of the greatest possible accuracy.

The theoretical justification for the preference of the Maddox-rod is usually based on two arguments: (1) that the prism-diplopia test is unsatisfactory because it gives false results if the dissociating prism is not placed with its axis in the correct direction and (2) that if both images to be superposed or aligned vertically do not fall on the foveae then there will be a stimulus for fusion. The reasoning behind the second argument is given by Cridland who said:[5]

> Any method of measuring heterophoria, and this applies to all tests, whatever the position of rest which they tend to give, may be falsified if the two images do not both fall on the maculae of the respective eyes which perceive them. For if the image of any object, and in particular the image of the object to which attention is directed, falls off the macula, the fixation reflex is immediately called into play, and the more vigorously if the object stands out more clearly from the background.

A basic difference of opinion is found in this quotation from Savage:[36]

> The Maddox-rod is objectionable in all tests of the recti for the reason that a part of the streak of light, whether it be vertical or horizontal, will fall on the field of binocular fusion, unless the error be great. The false image, whatever may be its character, should never be on any part of this field; otherwise a greater or less effort at fusion will be made.

The latter opinion seems to be the correct one because Westheimer and Mitchell found that, "disparate visual configurations may be quite dissimilar in shape and contrast in the two eyes and may even be separated by about 100 msec in time and several degrees in the vertical direction and yet elicit normal horizontal vergence movements.[43] Even more telling than this is their statement that, "a vertical line segment as short as 3 min of arc in one eye presented in disparity with a vertical line of any length in the other eye still elicits horizontal vergence movements." These observations should disqualify the Maddox-rod as a means of dissociation.

Phoria and fixation disparity. Fixation disparity is always measured without dissociation. For this reason, there can be no direct connection between fixation disparity test results and those for heterophoria. In spite of this, the name associated horizontal phoria has been used to describe the forced vergence which reduces the fixation disparity to zero.[28]

When the associated phoria is compared with the conventional phoria, for the same subject, they are sometimes similar and sometimes quite different.[16] Comparative data can be seen in Figure 2, parts C and D, where the results of conventional phoria measurements are shown along with the fixation disparity curve. The arrow labelled MR indicates the phoria found by means of the Maddox-rod test while that labelled CT indicates that found by the cover test. It is worth remarking that, in part C, the subject had to force his eyes to converge by 7 deg in order to eliminate a disparity due to overconvergence. Not only is it odd that forced convergence is required to cause a relative divergence in the disparity but it is also remarkable that a vergence change of 7 deg should be required to eliminate a vergence error of 7 min of arc. (As far as can be determined the reason for this relationship is not known and this may be the first time that anyone has remarked upon it.) This sort of evidence should have been enough to show that any connection between associated and dissociated phorias was tenuous. Further proof of this is found in some of the results to be presented in the following chapters.

V. PHOROMETERS

All phorometers comprise a dissociating device and a displacement measuring device. The name phorometer is usually reserved for a self-contained unit. All phorometers require some sort of test object, or target, for the subject to look at. Although the target is a necessary part of phorometry, it is seldom considered as part of the phorometer.

The first phorometer was invented by Stevens.[40] It comprised two prisms of equal power, one placed before each eye. The prisms were mounted in a metal holder which constrained them to a rotary motion with the axis of rotation being normal to the plane in which the prism lay. The two prisms were geared together by an idler wheel. An actuating rod was attached to one of the prisms such that the operator could change the orientation of the prisms. To measure the lateral heterophoria, the prisms were turned so that one was base up and the other was base down. The images seen by the subject were thus dissociated and the operator then moved the prisms, by means of the rod, until the subject reported that the images were in vertical alignment. A scale marked on the phorometer indicated the amount of the phoria. With this system, the amount of vertical dissociation varied as the lateral prism power was changed.

The first phorometer to use the Maddox-rod was that devised by Prince.[31] This was simply a hand-held device in which a Maddox-rod was placed behind the two prisms of a rotary prism unit. Thus the unit comprised a Maddox-rod and a Risley rotary prism mounted on a handle so that both were placed before the same eye. No levelling device was provided.

The Wilson phorometer comprised a dissociating prism before one eye and a Risley rotary prism before the other.[36]

Savage's phorometer was an improvement on the Wilson unit in which the dissociating and the rotary prisms were placed before the same eye. It also included a spirit level and was rigidly supported on a stand.[36]

The phorometer introduced by De Zeng was the prototype of all modern clinical phorometers.[11] It was a multiple purpose unit, see Figure 3, in which all the commonly used phoria measuring devices were included. Associated with each eye was a Maddox-rod, a dissociating prism and a rotary prism.

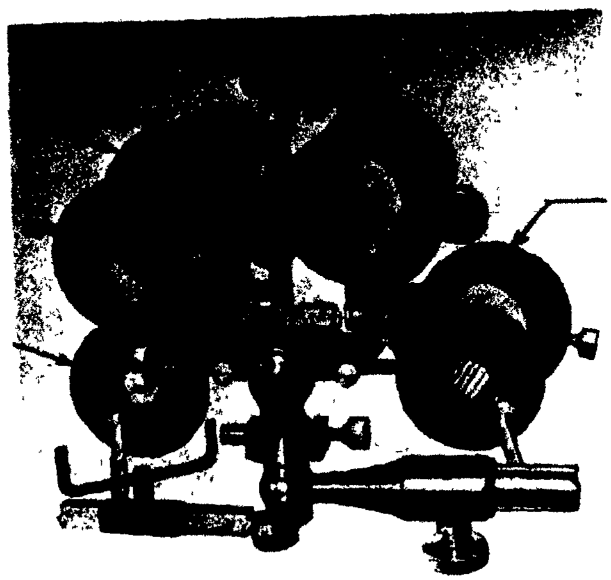

Figure 3. A multiple purpose phorometer with (A) Stevens phorometer attachment, (B) Maddox graduated multiple rods and (C) universal double rotary prism unit.

Each of these devices was in an independent holder which pivoted about a common shaft. By this means, any or all of these devices could be placed before the eye. The choice of the combination, and the eye before which they should be placed, was left to the operator. A Stevens phorometer, which could be clipped into place, was also included. It is current practice to provide a lens changing unit in front of each eye in addition to the phorometer elements.

Any of the above phorometers can be used for near vision as well as for the distance but one near distance phorometer which deserves mention, because of its popularity, is the Maddox wing test. Its description may be found in Duke-Elder.[15]

In 1945 Quereau and Putnam introduced an instrument which they called a tropophorometer.[32] The reference objects were two small lamps mounted on pivoting arms. Each arm was hinged to pivot about the centre of rotation of the eye with which it was associated. The angular position of the arm was determined from scales attached. Each lamp was seen only by the eye associated with it because of the lamp's construction. The tropophorometer must be used in the dark, except for the cover test. If the lamp used to locate the direction of the deviating eye is flashed in the dark, it is as if a cover were used. This device is very useful in that the fixating eye may be directed in any direction and the phoria, associated with that direction of regard, measured.

The phorometer which was used for this study was developed in 1972 and is based on a computer-controlled Risley rotary prism.[22] The phorometer's operation can be programmed to execute any test which calls for a rotary prism.

CHAPTER III

A COMPUTER-CONTROLLED PHOROMETER

The phorometer which was used throughout this study did not differ from its predecessors in its essential parts. Where it did differ was in the use of a motorized rotary prism whose prismatic power was adjusted by means of a digital computer. The outstanding feature of this arrangement was that the phoria could be quickly determined and that the test could be repeated with no appreciable delay.

The phoria tests performed with this unit were, with one exception, programmed versions of the tests most commonly used. The most explicit description of each test was sought out and used as a guide for programming. No test description was found to be detailed enough for programming purposes so I was obliged to define each test procedure myself. The programs prepared for this study are probably the first complete descriptions of the conventional phoria tests.

The subject whose phoria was being measured was the one to judge when the phoria was cancelled by the rotary prism. These tests are therefore all subjective in nature. The subject indicated the moment of cancellation by means of a hand-held switch and the current values of time and prism position were recorded by the computer. In this way, reaction time errors were kept to the absolute minimum.

The automatic recording of data and the ability to change the prism's power at any required rate enabled the test to be repeated without delay. It was thus possible to record a sequence of phoria measurements with a minimum time interval between them. The term "sequential measurement of heterophoria" was used to describe this procedure.

The phoria measuring prism was a Risley rotary prism driven by a stepping motor. The name "stepping prism" is used to describe such a device. Some recent publications contain descriptions of this device and its uses.[20,21,22] The original stepping prism was not suited to phoria measurements because the prism's power changed too much with each step. For this reason, a new stepping prism was designed in which the greatest single step was 0.1Δ. This differed from its predecessor in that a speed reducer was interposed between the stepping motor and the rotary prism. Each motor winding was also provided with a parallel capacitor and a current limiting resistor so that the maximum operating speed could be obtained. Under ideal conditions it was possible to slew the prism at a rate of 1 step/msec. The prism could be altered from zero to its maximum power of 30Δ in slightly more than 0.3 sec. Since the prism's base could be moved either to the left or to the right the total range of prism power was ±30Δ. The photograph in Figure 4 shows the stepping prism unit partially disassembled. The circuitry on the printed circuit board is used to convert the TTL logic input into a motor step output. Two input channels are provided, one for the direction of motor rotation and the other for the performance of a single step.

Previous work with the stepping prism showed that too much computer time was wasted in single stepping the motor. This complicated the programming and also left little time for executing other programmed routines. To overcome this problem, a special interface was designed which acted as a dedicated motor controller. This controller accepted instructions from the computer's input/output bus and executed them with regard to the motor's direction of rotation, the number of steps to be made and the stepping speed. The circuit diagram for this interface is shown in Appendix B. In essence, the motor

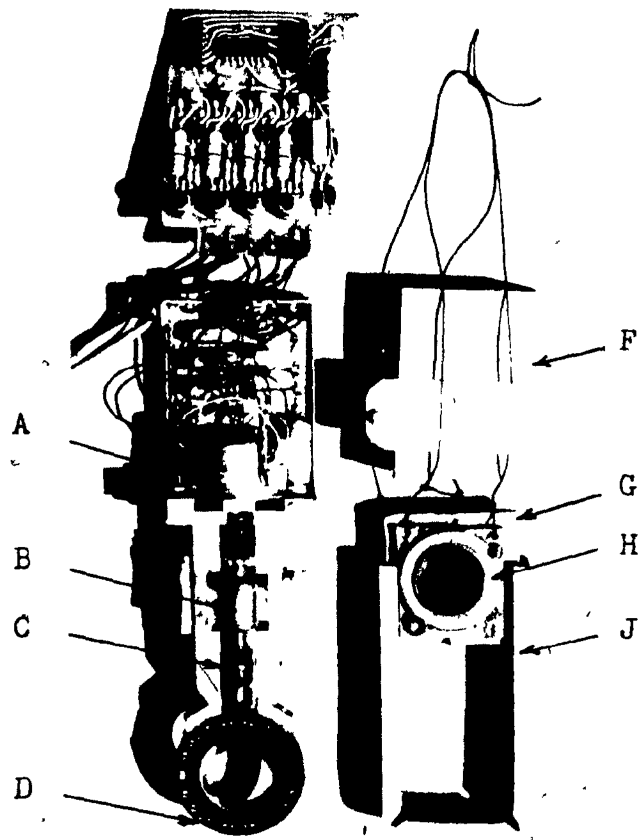

Figure 4. Stepping prism unit shown partially dis-assembled. Parts indicated are (A) stepping motor, (B) speed reducer, (C) flexible coupling, (D) Risley rotary prism, (E) motor controller, (F) cover, (G) carrier, (H) 6Δ dissociating prism and (J) slide ways.

controller is a pulse generator and counter circuit. The computer's instruction is decoded into the number of steps to be made and this is set as the count limit. The instruction starts the pulse generator and with each pulse the motor takes one step. When the correct number of pulses has been counted the generator is turned off. At the same time a flag is set and an interrupt request is made. The instruction to the controller also includes the desired stepping direction and a means of selectively channelling the pulses to two motors. A separate instruction is required for setting the stepping rate. This need not be re-issued until a change in rate is desired. A pre-set counter outputs a pulse after the desired number of input pulses have been summed. The counter is arranged so that pulses can be passed on after a count of any integer between 1 and 100. The slowest motor speed was therefore 0.01 times the fastest one. This control system proved to be trouble free and well suited to its task.

A PDP-8L computer was used to control the actions of the prism and to perform the other tasks associated with the phorometer. A Lab-8 peripheral device control system was also used. A teletypewriter was used for operator input and hard copy and punched tape output. An X-Y point plotter was used for preparing graphs.

The programming of the phorometer was for the most part the programming of the movements of the rotary prism. The actual programming details depended on the type of phorometer that was to be simulated. Certain programming features were common to any type of phorometer, such as the plotting of the response values as they were recorded and the typing out of the numerical values when the test was completed. Other details were quite specific, such as the operation of the covering screen during the automatic cover test.

The working part of the phorometer, that is to say the part which the subject looked through, comprised the stepping prism and the dissociating device or devices. These were supported on a floor mounted frame. To allow for variations in interpupillary distances, the elements of the phorometer were mounted so that they could be displaced laterally along a horizontal beam placed above the subject's brow. This arrangement is shown in Figure 5. Vertically mounted slide ways are seen in this figure. These slide ways were used for holding dissociating devices. One set was permanently mounted on the front face of the stepping prism unit while another set was used either for holding a dissociating device before the other eye or else for supporting the solenoid operated screen. The screen is shown in both the open and shut positions in Figure 5.

The devices to be placed in the slide ways were first fastened to a carrier. This carrier was free to slide up and down in the ways, if this were necessary for the test. A solenoid operated clamp, shown in Figure 6, was placed directly above the phorometer elements. Strings attached to the carriers passed through it. By this means, the carriers and the dissociating devices mounted on them could be held out of the line of sight and could be released at the appropriate time to fall in front of the subject's eyes. A string, attached to a switch, was pulled to open the clamp that held up the carriers.

The input and output of control signals from the computer to the phorometer were handled by the Lab-8's AXO-8 peripheral controller. Of the devices provided by the AXO-8 only the following were used:

Figure 5. The computer-controlled phorometer with the solenoid operated screen and the dissociating device in its carrier. On the left the screen is in the cover position and the carrier is in the dropped position.

Figure 6. The phorometer and its supporting stand. The view on the right is that seen by the subject. The solenoid operated clamp is seen near the top. The push button switch is resting on the bottom beam. The vertical board is used as a vibration damper.

1. One analog to digital converter with a 9 bit resolution.

2. Two digital to analog converters with an 8 bit resolution. These were used to position the pen on the X-Y plotter.

3. Two Schmidt triggers, one of which was used to accept the subject's responses. The other was used to detect the plot completed pulse given by the plotter.

4. Two relay outputs, one used to enable the plotter and the other to control an external device.

5. One pulse output channel used to request a plot from the plotter.

The choice of peripheral devices depended on the type of phorometer that was being simulated. A hand-held switch was used as the input from the subject. For some tests the subject controlled the prism's power himself by means of a hand-held potentiometer. The voltage from the potentiometer was used to indicate the prism power desired.

The software for controlling the phorometer was developed in stages. All programs and subroutines were written expressly for this project with the exception of a single precision divide subroutine which was supplied with the computer. The memory requirement for the most complex program was 850 words, each of which comprised 12 binary bits.

The original programming was written to perform the prism-diplopia test. As other tests were programmed the previous program was modified to suit and therefore much of the software developed is common to all of the tests.

A flow diagram for the prism-diplopia test is given in Appendix C along with the required switch register settings that enable the options included in the program. A copy of an original data plot along with its data listing, as typed, is found in Appendix G.

When the phorometer was first used, the dissociating device was fixed in place. It was soon realized that this was a cause of uncertainty in the starting conditions of the test. This was because the subject's eyes were dissociated for an indeterminate period before the test was started. This was unavoidable because the subject had to look through the phorometer while it was being adjusted. To overcome this problem and to enable the time course of the phoria to be measured, a technique called the "drop start" was adopted. For a drop start, the dissociating or other devices were held up out of sight until testing was to start. At that time they were released to fall in place in front of the subject's eyes. A voltage transient caused by the releasing solenoid was used to signal the start of the test.

CHAPTER IV

THE PROGRAMMED PHORIA TESTS

The phoria tests performed during this study were all executed under almost identical test conditions. The phorometer was never moved and the test distance and room lighting remained constant. Because of space limitations all of the tests were performed at a distance of 40 cm. The illuminance on the test target was 30 fc except for one Maddox-rod test in which the room was in total darkness. The test target most frequently used was a large sheet of white paper with a 2 mm diameter black dot at its centre. The subject's field of view was so limited by the frame of the stepping prism unit that there were no significant clues for binocular fixation other than the dot and the grain of the paper.

The subject was seated at the phorometer with his chin in a rest. The chin rest was adjusted until his eyes were on the same level as the centre of the rotary prism and the prism was moved laterally until the subject looked through its centre. If the subject normally wore an ophthalmic correction he was asked to wear it if it were habitually used for near vision.

If the subject were not familiar with the test to be performed, he was told what to do and was sometimes given a preliminary demonstration. He was advised of the importance of always looking at the motionless image and that he should resist looking at the other one. When using the dissociating prism, it was sufficient to say that he must always look at the lower image. The proper use of the push button switch was also demonstrated and if he were to adjust the prism by means of the potentiometer, he was shown how it worked.

Aside from instructing the subject, the operator's preliminary duties were to place the graph paper in the plotter, start the program running, plot the corner reference points on the graph and set the switch register to indicate the desired actions to the computer program.

The operator was required to look at the scale on the prism's face before and after the test. If the prism were not set at zero power the operator set it so with the direction of approach to zero being from base left toward base right. This was necessary because of backlash calculations. If there were no error in the prism's action during the test, the prism would be found at exactly the same position at the end of the test. This checking method was based on the principle of the check sum. A record was kept during the test, by the program, as to where the prism ought to be. The prism was returned to the zero position, with due respect being paid to backlash, at the end of the test. The number of steps necessary to return to zero was calculated from the prism's supposed position at the end of the test. Any errors in the prism's response during the test were shown if the prism were not found at zero. If an error were found the results were discarded.

The results of the phoria test were recorded in two ways: (1) by means of a graph produced on the X-Y plotter as the test proceeded and (2) by means of a typeout of the data when the test was concluded. Additional data analysis could be requested after the typeout and the results of this analysis were recorded graphically by the plotter. Two auxiliary plot routines were developed during this study, one for averaging and the other for a special analysis called "delta-vergence". A punched paper tape was produced during the typeout. This was used as input data for further analysis.

It was found that the points, as plotted, did not give a good picture of the results so it was usual to join them with an ink line before studying the graph. Since the points were dark blue a lighter colour was used so as not to obscure them.

The typed data was presented in a single column with the signed number of steps from zero preceding the time at which the response was made. The time was shown in tenths of a second. The length of the typeout became quite unwieldy when many responses were made. The typeout served a useful purpose because sometimes the points were not properly plotted on the graph.

An auxiliary routine which was particularly useful was that used to convert the data into a more readable form. A FORTRAN program was prepared to run on a larger computer, a Control Data 6600, and this took the data from the punched paper tape and converted it into the prism power in tenths of a diopter at the time of the response. The number of prism steps corresponding to a given prism power is shown in Appendix D along with the FORTRAN program.

I. THE PRISM-DIPLOPIA TEST

The prism-diplopia test was the first to be programmed for the phorometer. There was no special reason for this choice other than that it seemed to be the easiest to set up. At first, the 6Δ dissociating prism was placed before the eye not looking through the stepping prism. Later Savage's advice was followed and both prisms were placed before the same eye. Finally, the dissociating prism was mounted in a vertical guide so that it could be dropped in front of the subject's eye at the start of the test.

The prism-diplopia test procedure was inadequately defined in the ophthalmic literature. It was therefore necessary to perform some preliminary studies to determine the most reasonable test procedure. The results of this study have already been published.[22] The conclusions were that the fastest operating speed consistent with the subject's ability to respond gave the most phoria information. Time delays, whenever necessary, were best kept to a minimum and the cancellation of the phoria should be approached alternately from opposite directions.

The cycle chosen for the test was: (1) to make a continuous change in prism power in one direction until the subject indicated alignment by actuating the switch; (2) to record the prism's position and the elapsed time since the start of the test whenever the subject actuated the switch; (3) to instantly alter power by 50 steps in the same direction as the prism's previous motion and (4) to change the prism's direction of motion and proceed as in step (1). This cycle was repeated until the test was stopped by the operator.

The name "offset jump" was coined to describe the abrupt change in prism power which occurred after the subject's response. The amount of the offset jump was always 50 steps. Starting the jump from zero power, this corresponds to 4.6Δ.

The operation of the system is best understood by means of a description from the point of view of the subject.

The subject saw a black dot on a field of white. Suddenly two identical dots were seen, one directly above the other. The double images were caused by the dropping in place of the dissociating prism. Shortly thereafter the upper image jumped to one side of the lower one and then began to move toward alignment again. When the images were aligned vertically the subject pushed the switch momentarily. The upper image was then seen to move to a new position by an offset jump having the same direction of motion as before. After this the dot remained motionless for about 0.5 sec and then started to move back toward vertical alignment again. The rate of movement was about 2.0Δ/sec. When alignment occured again the subject pushed the switch, the offset jump was made again only this time in the opposite direction to the previous one. The test continued in this way until the operator stopped the test by depressing the space bar on the teletypewriter. The subject then saw the dot move to one side until it stopped and the test was over.

A set of results for 5 subjects is shown in Figure 7. They are typical in that they all show a fairly rapid change from zero to some final value which is relatively stable. The curve for D.S. has drifted to 3.5Δ of exophoria after 7 sec have elapsed. Thereafter the average value is 3.8Δ with the standard deviation being 0.4Δ. Subject J.C. is seen to take longer to arrive at a stable average value. It is reasonable to assume that the initial drift from zero has finished after 37 seconds. Since the average value is in the order of 6.5Δ it might be assumed, incorrectly, that the longer time was required because the phoria was greater. The curve for B.A. shows that there is no necessary relationship between the amount of heterophoria and the time required for the subject to arrive at this value. It took B.A. 17 sec to reach his average phoria of 11Δ.

As an example, the typeout of data for subject J.C. is shown in Appendix E. To conserve space the list was arranged into columns. The same data arranged by the FORTRAN program is also shown.

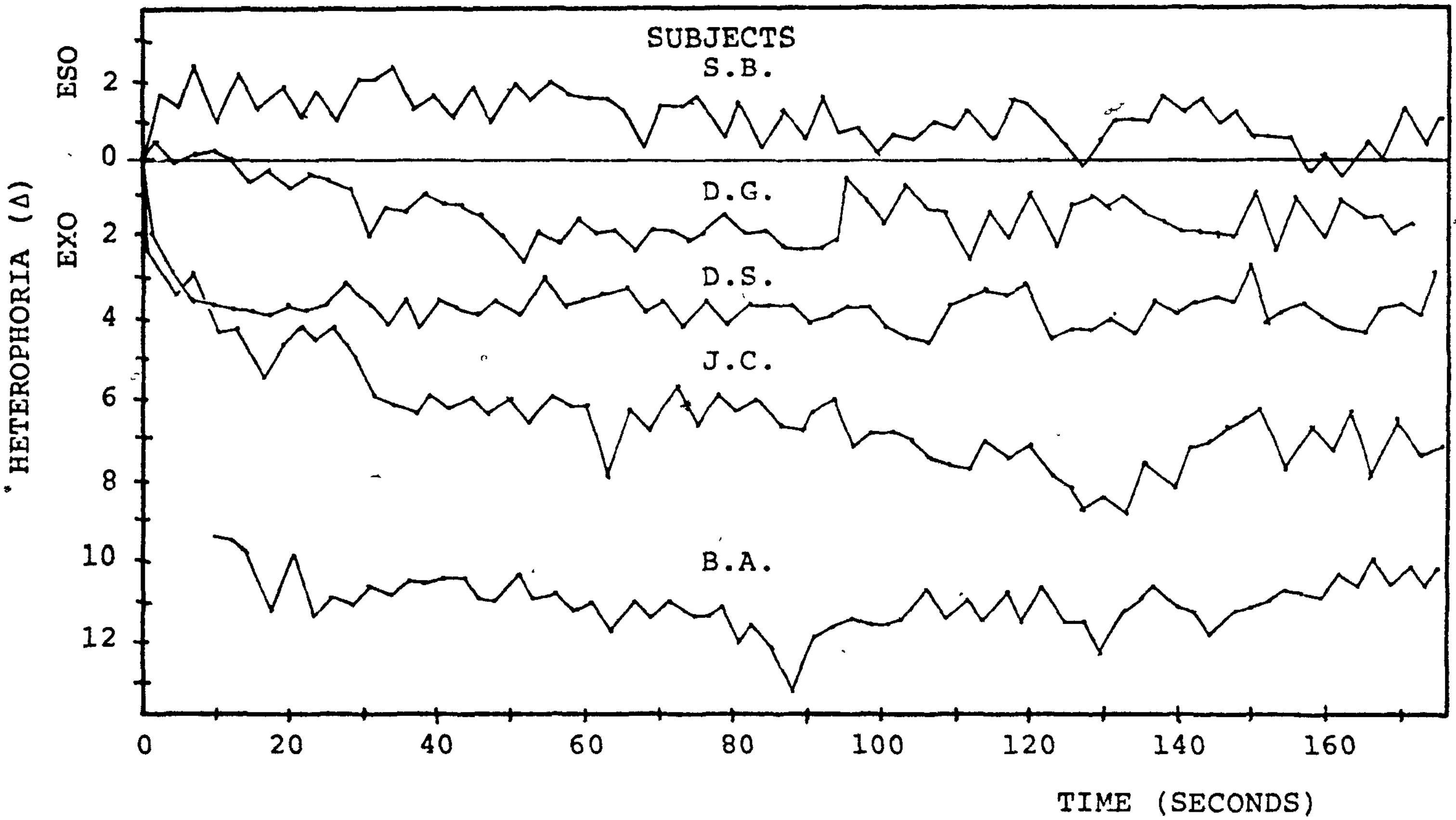

Figure 7. Phoria measurements for 5 typical subjects. Prism-diplopia method was used.

Some atypical results are shown in Figures 8 and 9. Figure 8 shows two subjects who were esophoric and who, it was later discovered, had suffered from convergent strabismus as children. Subject J.L. had been operated on for the condition and neither subject showed any obvious sign of excess convergence. The thing that makes them atypical is the instability of the phoria. For example, subject J.L.'s initial phoria is 9Δ after 5 seconds. There is then a decrease in esophoria until 120 sec later the average value is about 3Δ. In the case of J.F., the phoria's initial value of 11Δ soon falls to about 8.5Δ and then rises again until it is in the order of 13Δ. This rising and falling continues throughout the test.

The results for two exophoric subjects are shown in Figure 9. The curve of A.L. is considered atypical because of its zig-zag form. This response pattern is not invariable as can be seen after 140 sec have elapsed. The response curve of W.L. is remarkably continuous from 7 to 45 sec after the start of the test. Thereafter it becomes very choppy and shows a reduction in exophoria of 4Δ. An interesting observation is that if the straight portion from 7 to 28 sec is projected backwards it intercepts zero time at zero prism power.

II. THE FUSED-IMAGES TEST

The test described by the name "fused-images" is a new procedure which can be applied to the measurement of lateral heterophoria. The characteristic which sets this test apart from all others is that it does not use a dissociating device and yet the subject is in a state of diplopia most of the time. The means employed to disrupt fusion, and thus force a dissociated position to be adopted by the eyes, is the offset jump. When the prism's power is changed quickly, as it is during an offset jump, the vergence system does not have time to respond and so

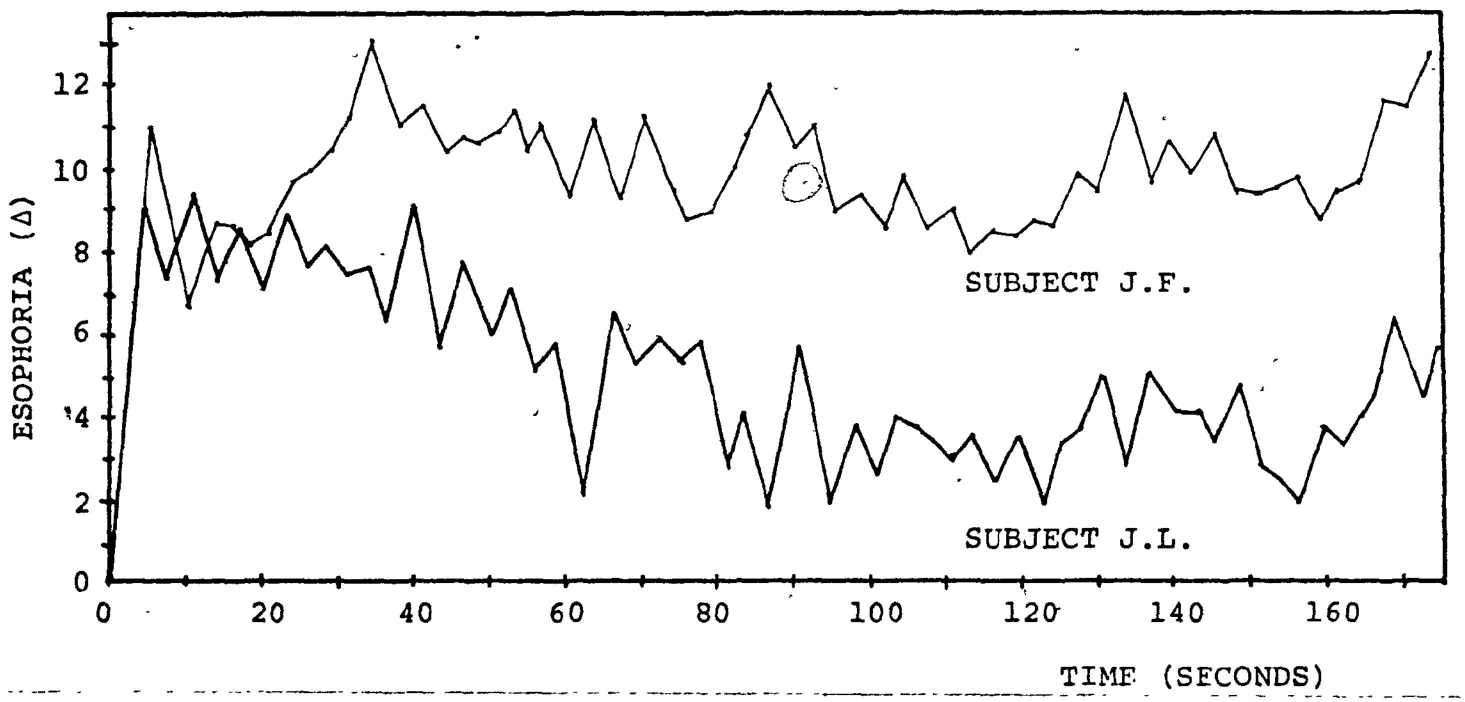

Figure 8. Phoria measured by the prism-diplopia method. Two subjects whose esophoric responses were atypical.

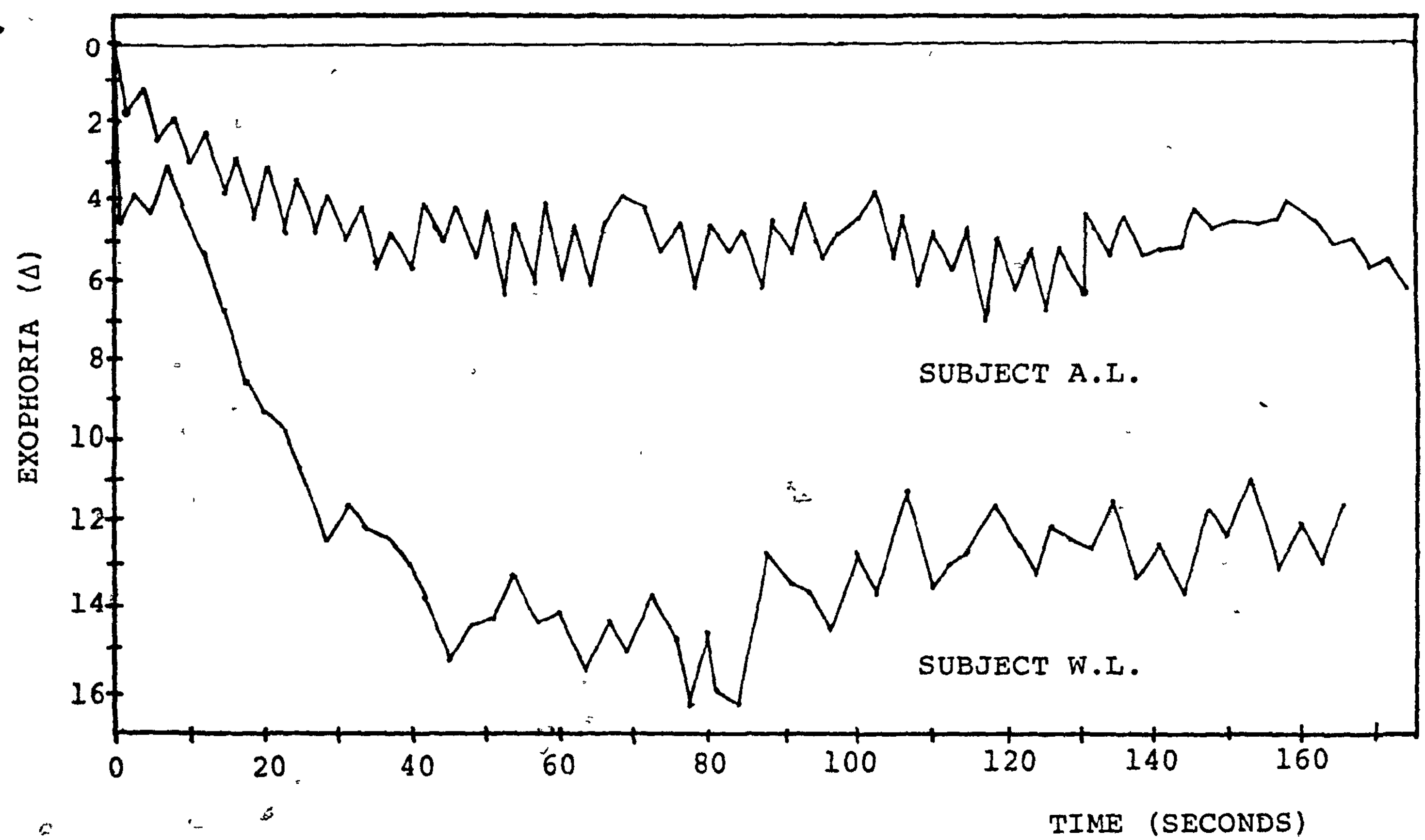

Figure 9. Phoria measurements made by the prism-diplopia method. Two atypical subjects with exophoria.

for a short time the subject will suffer diplopia.

In the fused-images test, the subject actuated the switch whenever he saw only one image; that is to say when fusion had occurred. Shortly thereafter an offset jump was made at which time two images were seen again. Immediately after the offset jump, the prism began moving, at a rate of 2.4Δ/sec, toward its power just before the jump. When fusion occurred again the switch was actuated and so on till the end of the test. The offset jumps were performed on alternate sides. All of these operations were performed at the highest speed consistent with reliable operation. The programming for this test method was similar to that already described except that no delay was made between the end of the offset jump and the return toward alignment of the images.

During this test the images are dissociated most of the time and the quicker the response to fusion the less the images will be fused. This test requires that the subject remain alert otherwise the moment of fusion will be lost. From the subject's point of view the test is rather like a game in which the object is to always see double. A subject whose vergence is moderately stimulated by this procedure will make about 130 responses during 175 seconds.

This test procedure presents the subject with a vergence stimulus of about 5Δ every time he actuates the switch. With each repetetion the vergence stimulus is in the opposite sense. It is obvious that this test is more a test of vergence responses than it is a test for lateral heterophoria. The remarkable thing is that it gives average values that are similar to those found by conventional phorometry.

Figure 10 shows fused-images results for two subjects who were typical when tested by the prism-diplopia method. Subject D.S. is typical of those who were responsive to the stimulus for a vergence change whereas V.V. is remarkable in that the stimulus seems to have been ignored. In fact V.V. behaves as if the images were dissociated by a dissociating device. Both of these subjects had normal vision without suppression so this behavioral difference was a characteristic of the subject and was not due to some visual defect.

Each of the subject's responses is plotted as a point on the graph. The treatment of the test results is shown in three sections, each occupying one third of the graph. The responses alone are shown in the left hand section. The responses and the prism power at any given time are shown in the centre section. The right hand section shows the responses joined by a line point to point.

The joining together of the plotted points does not always serve a useful purpose, as can be seen in the case of D.S. In order to extract meaning from a graph, it is much better to plot the midpoints between successive responses and to join these points together. This method of plotting has been adopted for all fused-images phoria results. The actual plotting of the points was performed by the computer. Response n was algebraically summed with response n+1 and the result was divided by 2 to obtain the mean, or midpoint. This value was then plotted at time n+1.

Averages alone do not describe the subject's response to the vergence stimulus. Since this test method had never existed before, it was necessary to create a method for showing the vergence change which had been stimulated by each offset jump. The method adopted was given the name "delta-vergence"

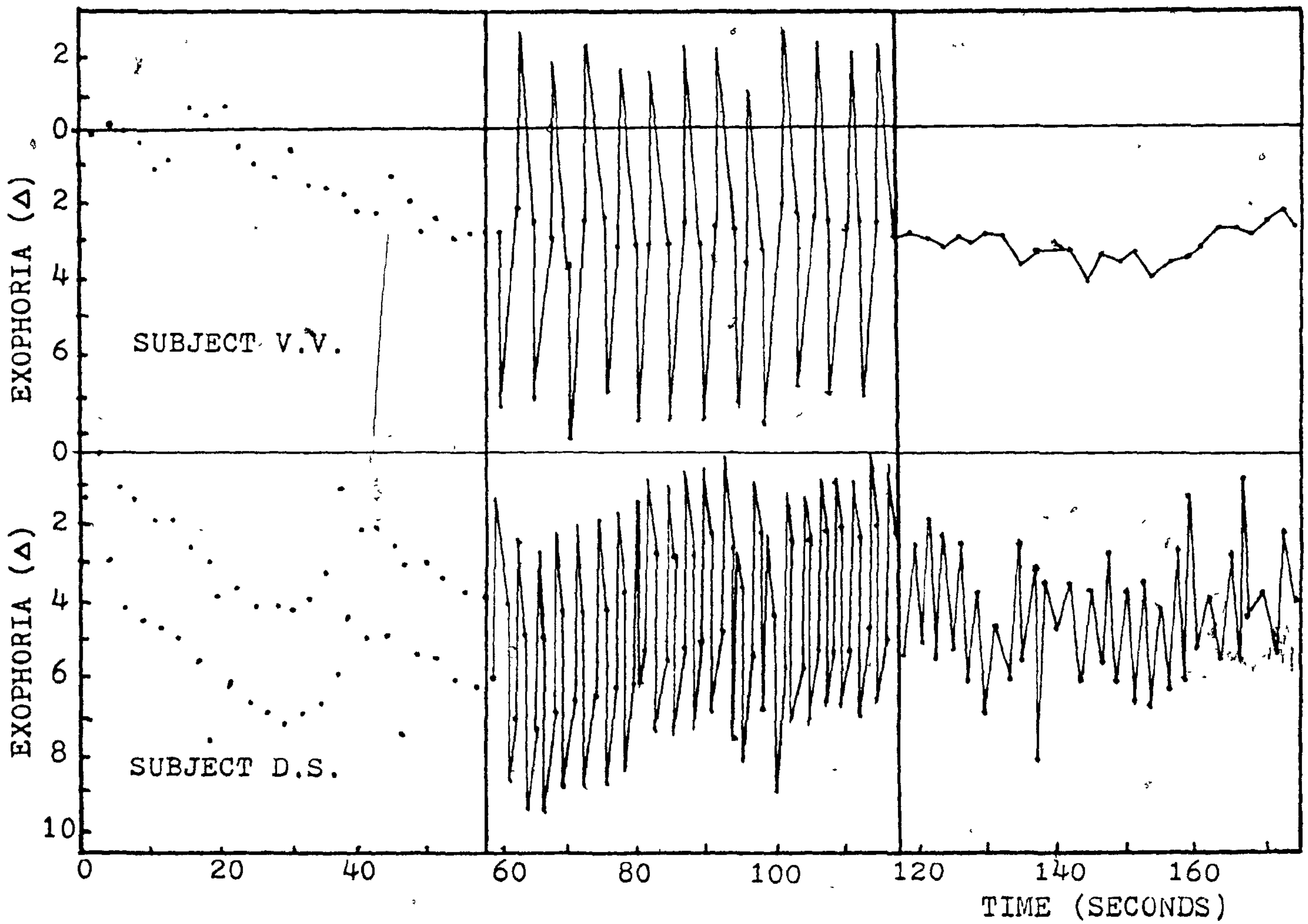

Figure 10. Fused-images phoria results for two subjects. The stimulus did not alter V.V.'s vergence whereas D.S. was strongly stimulated to make a vergence change. First 58 sec shows the points as plotted, the second shows the prism's power at any time and the third shows the points joined together.

because it consisted of a graph showing the magnitude and direction of the change in vergence. Delta-vergence was calculated by subtracting the response value at time n from that at time n+1 and then plotting the result at time n+1. If there were no change in vergence the value plotted would be zero. The phoria would not be shown through this graph but if there were a phoria change it would alter the delta-vergence values somewhat during the change.

An example of one subject's results re-plotted to show the midpoints and the delta-vergence is found in Figure 11. None of the original data is lost in this presentation. A phoria graph for this subject has already been presented in Figure 9. The phoria values obtained from the midpoints plot are seen to be similar to those obtained by the prism-diplopia test. Plotting details are shown in Appendix F.

III. THE AUTOMATIC COVER TEST

The results obtained with the different phorometer configurations were by no means clear cut. Methods which seemed to be above suspicion were found to be inherently variable. For this reason, it was decided to introduce the cover test as a means of determining the subject's true phoria. With this objective a computer-controlled cover test was devised. This was given the name of "the automatic cover test".

It will be recalled that the cover test differs from other phoria measuring methods in that one eye is blocked by a screen in order to produce dissociation. From time to time the cover is removed for a moment and then replaced. When the eye is not covered the subject is supposed to estimate the relative position of the dissociated images. The rotary prism must then be adjusted to eliminate any misalignment perceived

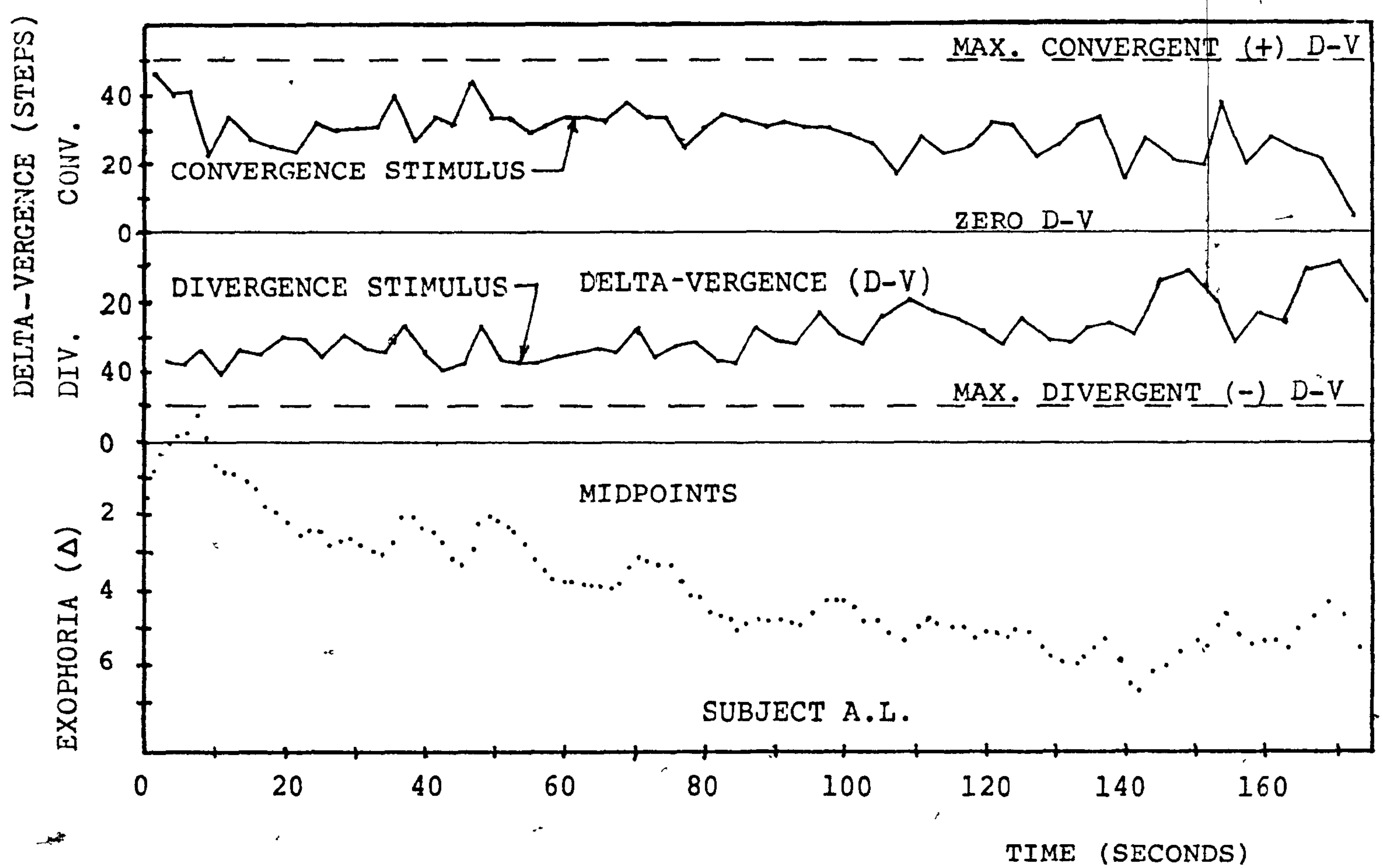

Figure 11. Delta-vergence and midpoints plots for fused-images phoria.

and the prism power that eliminates the misalignment indicates the amount of the phoria. The supposed merit of this method is that for most of the time there is no stimulus for fusion. Sometimes an additional dissociating device is used as in the case of the screen-Maddox rod test.

The phorometer was modified to perform the automatic cover test by providing a remote control system for adjusting the prism's power and by adding a solenoid operated screen which was placed before the phorometer unit. The programming was modified to suit the test procedure.

During the automatic cover test, the screen was removed from in front of the eye for 0.5 sec and then replaced. The subject adjusted the potentiometer, during the 3 sec in which the screen blocked his eye, so that the images were in closer alignment when the eye was next uncovered. The prism's power was recorded just before the next uncovering and its numerical value was plotted at the time of the previous uncovering. This cycle of uncovering and covering continued until the end of the test.

A series of identical recorded values indicated that the subject had brought the images into perfect alignment. To some extent the rate of change of values could be construed as a measure of how far out of alignment the images were. This interpretation was only valid for a skilled subject. Because of this, the data is only significant when two or more phoria values in sequence are identical. This indicates that the subject was satisfied with the correctness of the previous setting. Joining the points together, on the graph, does not necessarily indicate the time course of the phoria. In spite of this, the automatic cover test curves are similar to those plotted by the other methods.

Typical results obtained with the automatic cover test are shown in Figure 12. (Other results for subject A.L. are shown in Figures 9 and 11.) A 6Δ vertical prism was used as supplementary dissociation in addition to the screen. The starting position of the prism was not exactly at zero. The changes seen between 35 and 40 sec, on A.L.'s curve, are probably due to an error in the adjustment of the potentiometer.

The automatic cover test was performed with and without supplementary dissociation. The test without additional dissociation was found satisfactory but when the images were aligned to within Panum's fusional area the disparity could no longer be perceived.

IV. THE SEQUENTIAL MEASUREMENT OF FIXATION DISPARITY

The computer-controlled phorometer was also used for the determination of the associated horizontal phoria. Mallett's test for fixation disparity was used in conjunction with the potentiometer control of the prism. The disparity test unit is shown in Figure 13. The subject wore polarized glasses during the test. All details were seen binocularly with the exception of the two vertical lines of light seen above and below the X in the central circle to the left. Of these lines one was seen only by the left eye and the other only by the right. These lines were in perfect vertical alignment so if they were seen to be out of alignment it was due to a fixation disparity. If a disparity were seen it could often be eliminated by forcing the subject to change his vergence. This was done by adding lateral prism power before the subject's eyes. In this study the forced change in vergence was produced by the stepping prism. The subject adjusted the prism's power, by means of the potentiometer, until he saw the lines in vertical alignment. The prism power at alignment was taken as the associated horizontal phoria.

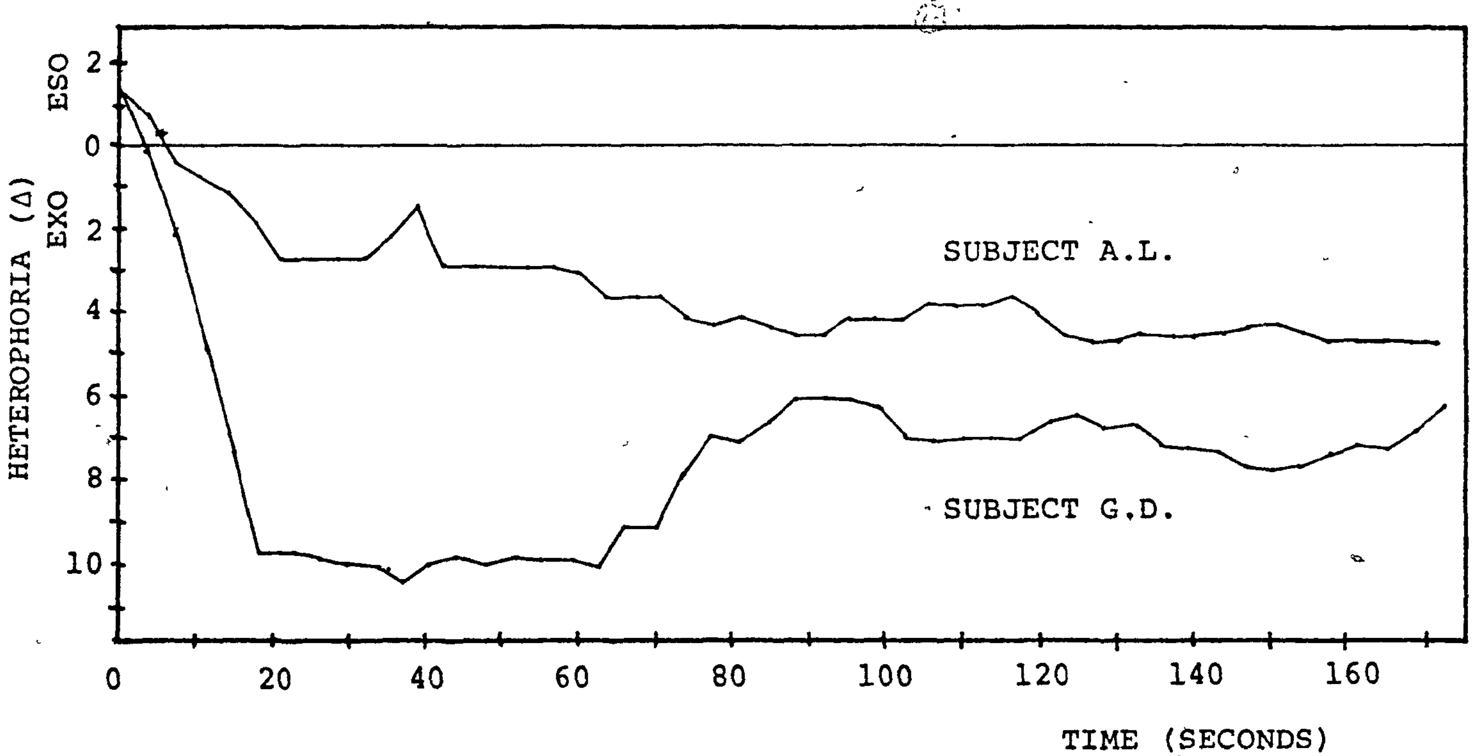

Figure 12. Automatic cover test results for 2 subjects

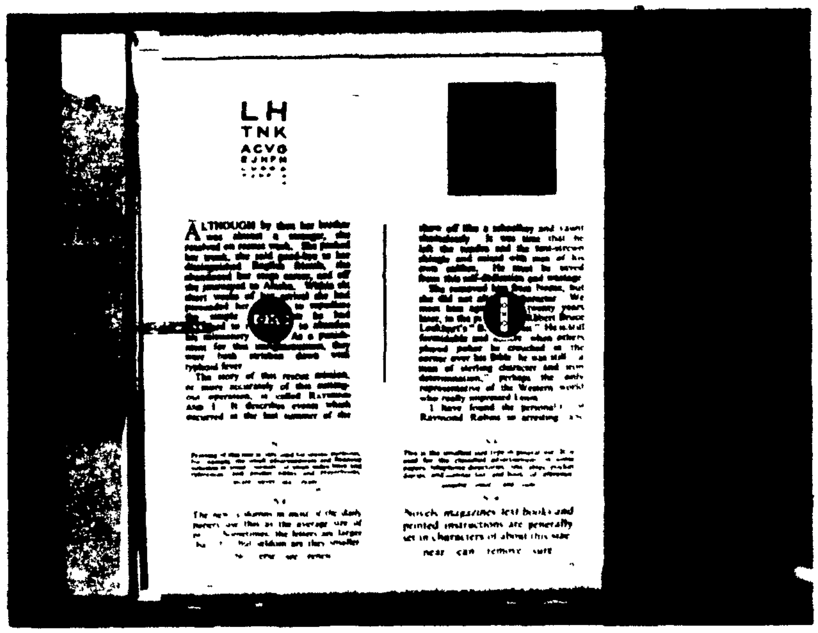

Figure 13. Fixation disparity test unit. The vertical lines within the dark circle to the left are those used to determine the lateral disparity. The plastic rod to the left of the circle supports the light emitting diode used as the object for the Maddox-rod tests. The lamp within the box was not turned on during the Maddox-rod tests.

Phoria plots for 3 subjects are shown in Figure 14. The points are not joined together because, in most cases, they are closely spaced. As in the case of the automatic cover test, two responses in a row with the same value indicate the phoria. The subjects were chosen to show different degrees of variability in the response pattern. The heterophoria of subject V.V. has already been shown in Figure 10 where it was determined by the fused-images method. Subject J.L. shows a remarkable difference in phoria compared with that determined by the prism-diplopia method as seen in Figure 8.

In order to measure the associated phoria sequentially, it was decided that the current position of the prism should be recorded every second. Thus, after starting the test, the subject adjusted the prism to obtain alignment and the prism power was recorded at one second intervals.

V. THE LENS DROP PHOROMETER

Once the system for the prism drop had been constructed, it was natural to extend its use to include dropping lenses. The synergy between accommodation and convergence has already been mentioned and this is often used to determine the AC/A ratio. If one were able to drop lenses in front of both eyes so that a sudden change in accommodation were required, the response to this step change should be a phoria change proportional to the AC/A ratio. In order to see what would happen when this was done, a second vertical slide unit was placed before the other eye. A -1.0 diopter lens was installed in each carrier and both were held up by the solenoid clamp. When the clamp was opened, the lenses dropped before the subject's eyes. The fused-images test method was used because there was no place left to put a dissociating device.

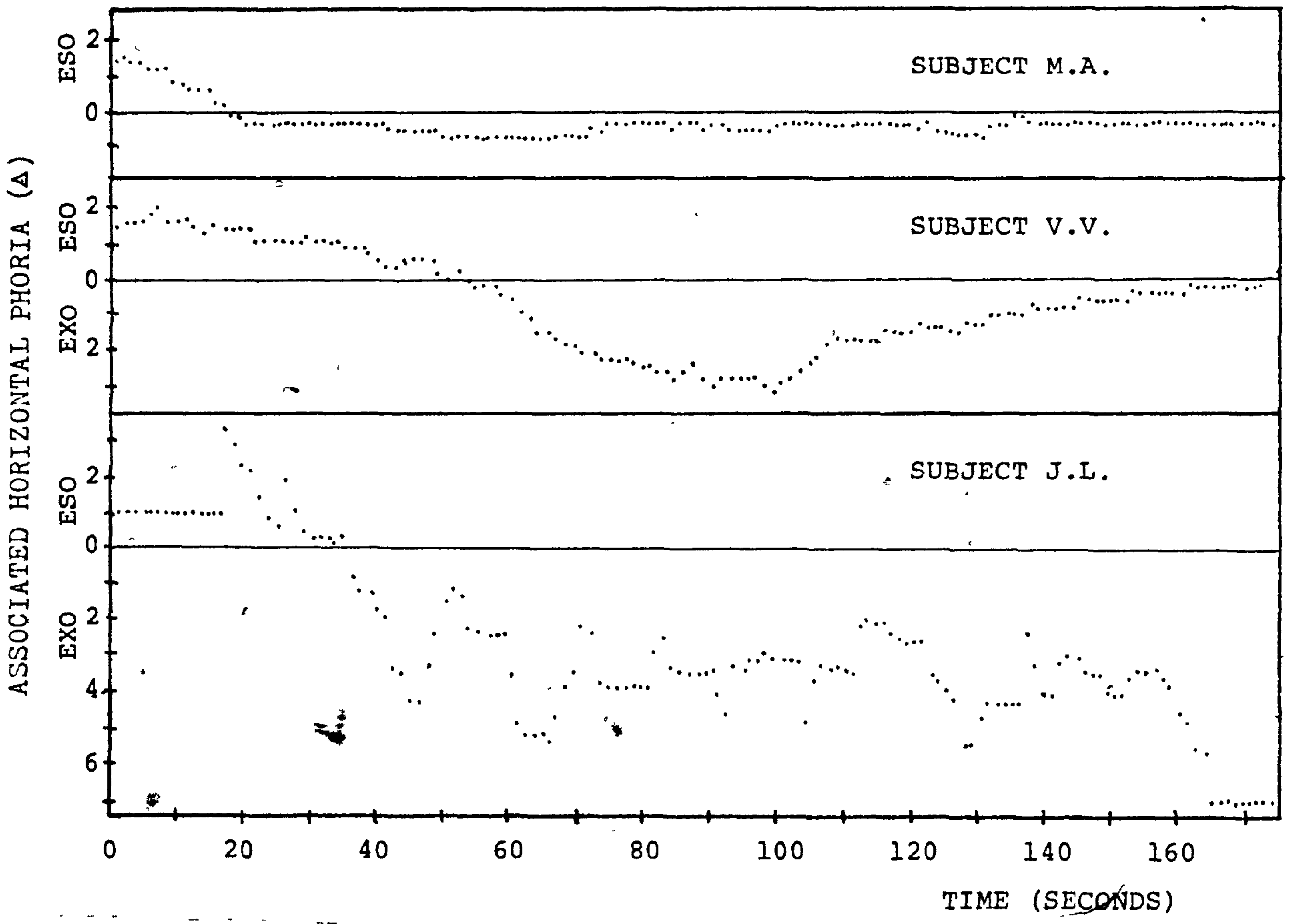

Figure 14. The sequential measurement of the associated horizontal phoria for 3 subjects. Subject J.L. suffered diplopia for the first 16 seconds.

The test was performed as a normal fused-images test until one minute had elapsed. At that time the lenses were dropped and otherwise the test continued without interruption. When the lenses were dropped, the eyes were forced to increase their accommodation by 1.0 diopter. The amount of accommodation required of the subject, throughout the test, could be adjusted by the addition of ophthalmic lenses in a trial frame.

CHAPTER V

RESULTS AND COMPARISONS

I. VARIABILITY

The results obtained with the computer-controlled phorometer show a certain amount of variability. Traditional methods of measuring the phoria also showed this but to some extent it was masked by the lack of precision in the measurements made. Gross phoria changes may be due to slewing toward an ultimate value or else to an inherent instability.

The variability caused by errors in judgement or habitual response patterns can cause local variations in the phoria. The subject's reaction time plays a part in this. Local variations in the values recorded have already been commented on in a recent publication.[22]

If the phoria amounts to more than a few prism diopters, there will certainly be an initial slewing toward the typical phoria value. When this slewing is finished, the phoria may be stable or unstable depending on the individual. If the test is repeated immediately, the subject repeats the same pattern of change even though the numerical values recorded may not be identical. If the test is repeated after a considerable lapse of time, the same pattern of change is seen and the numerical values found are similar to those previously recorded. On the other hand, a change in the test procedure can cause a considerable shift in the subject's response pattern and in the values recorded.

If tests are repeated after a short lapse of time, say ten minutes, the recorded values are often similar to those shown in Figure 15. Here two subjects have repeated the prism-diplopia test after a delay necessitated by the completion of

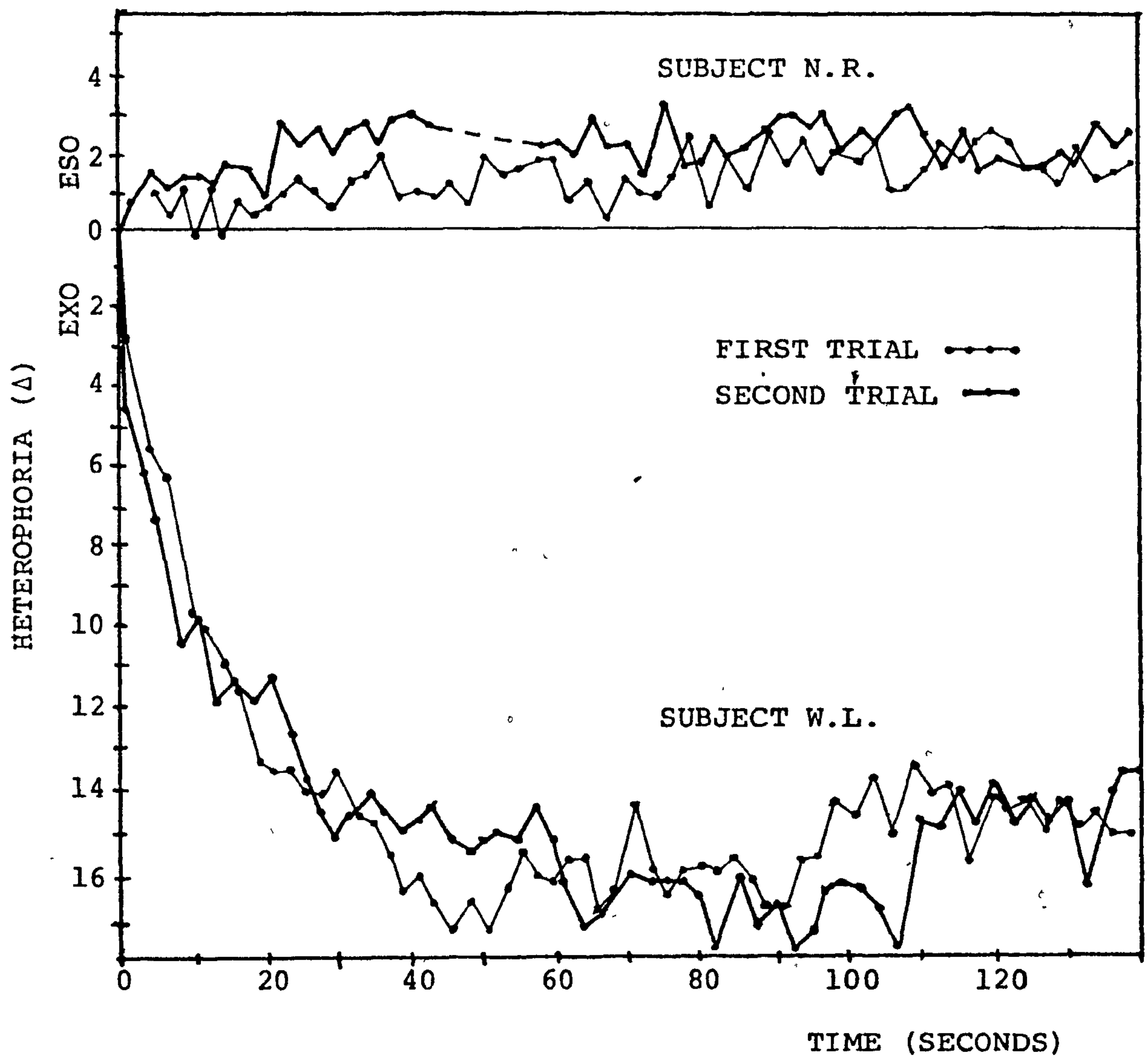

Figure 15. Lateral heterophoria tests repeated after 10 minutes. The prism-diplopia method with the prism drop start was used in both tests.

one test and the start of the next one. It can be seen that the repetition did not alter the response pattern to any extent. At the same time, it must be remarked that there is a real alteration in the recorded values during the course of any one test and that local dissimilarities can be quite considerable even though they may occur about some mean value.

If the tests are repeated after a longer time delay, such as is shown by the curves of Figure 16, it is obvious that the variations are of the same order of magnitude as those found after a minimum delay. Differences are seen but they are no greater than those found after short delays. An example of this is given by the two curves of subject W.L. in Figure 16. Although there is a lateral shift in one of the curves, it can be seen to be due to an arrest in the initial slewing of the eyes during the first 7 seconds. If the curve is shifted left to eliminate this, the graph looks similar to Figure 15.

As a general rule, a single test will reveal most of the characteristics of the subject's phoria. Repeated testing shows only minor differences from the first test, but if unusually large changes occur during the test, it is well to repeat it because these may not occur again. This rule is probably true for a manually operated phorometer but with such phorometers the procedure and the timing are not controlled and changes in these can cause changes in the phoria.

II. COMPARISONS

The phoria results obtained by different test methods are best evaluated by means of graphical comparisons. This method is also good when comparing the response patterns of different subjects to the same test. The comparison method of analysis has been found to be very revealing, particularly with respect to the degree and quality of dissociation associated with a particular test method.

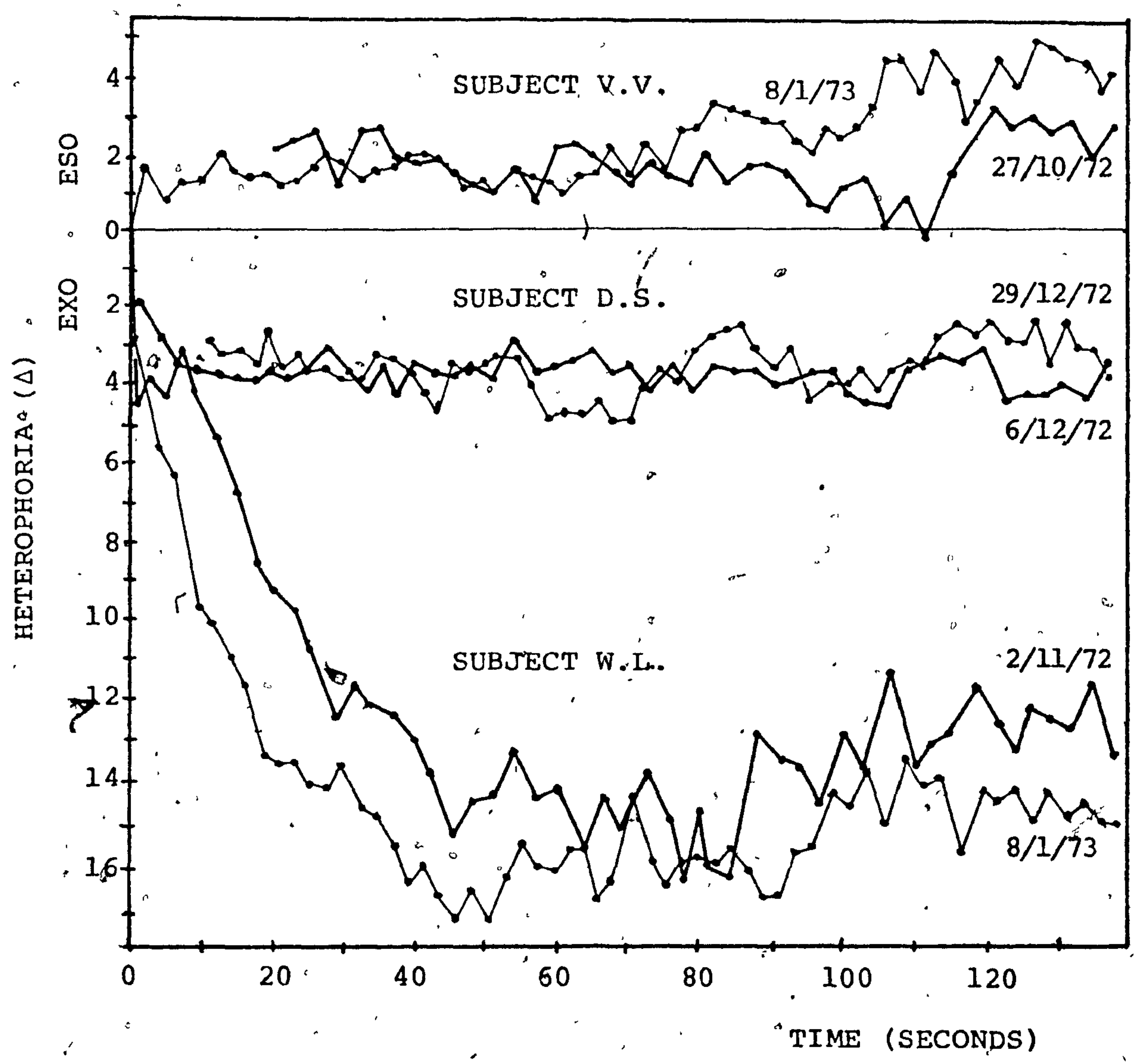

Figure 16. Lateral heterophoria tests repeated after a time lapse as indicated by the dates. The prism-diplopia method with the prism drop start was used for all tests.

Prism-diplopia and fused-images. In some cases, the results obtained by the prism-diplopia method and the fused-images method are quite similar. This can be seen in Figure 17 where the results for two subjects have been obtained by both methods. Although subject A.L. slews faster initially by the prism-diplopia method, the values recorded are similar after 80 seconds. This is also true for subject D.S. except that the initial change is over after 8 seconds.

Examples of two subjects whose phorias are quite different are shown in Figure 18. The curves for L.F. are in some respects similar but the average response by the fused-images method is seen to be more esophoric by about 2Δ. In the case of V.V., the difference is more marked and is in the order of 5Δ more exophoric. The prism-diplopia curves for both subjects are seen to be quite similar. This demonstrates that the use of only one test method does not give as much information about the subject as these two different tests do. Subject L.F. complained of asthenopia while V.V. had no visual problems.

A portion of the record of V.V. is repeated in the right hand graph (B) of Figure 19. The upper graph (A) for the same subject shows the delta-vergence analysis applied to the fused-images method data. The subject's vergence system is evidently not stimulated by the offset jumps. The data on the left hand side of the figure shows the same analysis applied to another subject. Subject J.G. is seen to be strongly stimulated by the offset jumps.

The delta-vergence analysis procedure may be used out of its original context as is shown in graphs (C) of the same figure. The data gathered by the prism-diplopia method has been analysed as if it had been gathered by the fused-images method. It is interesting to note that the curves seen in portions A and C are opposites for the two subjects.

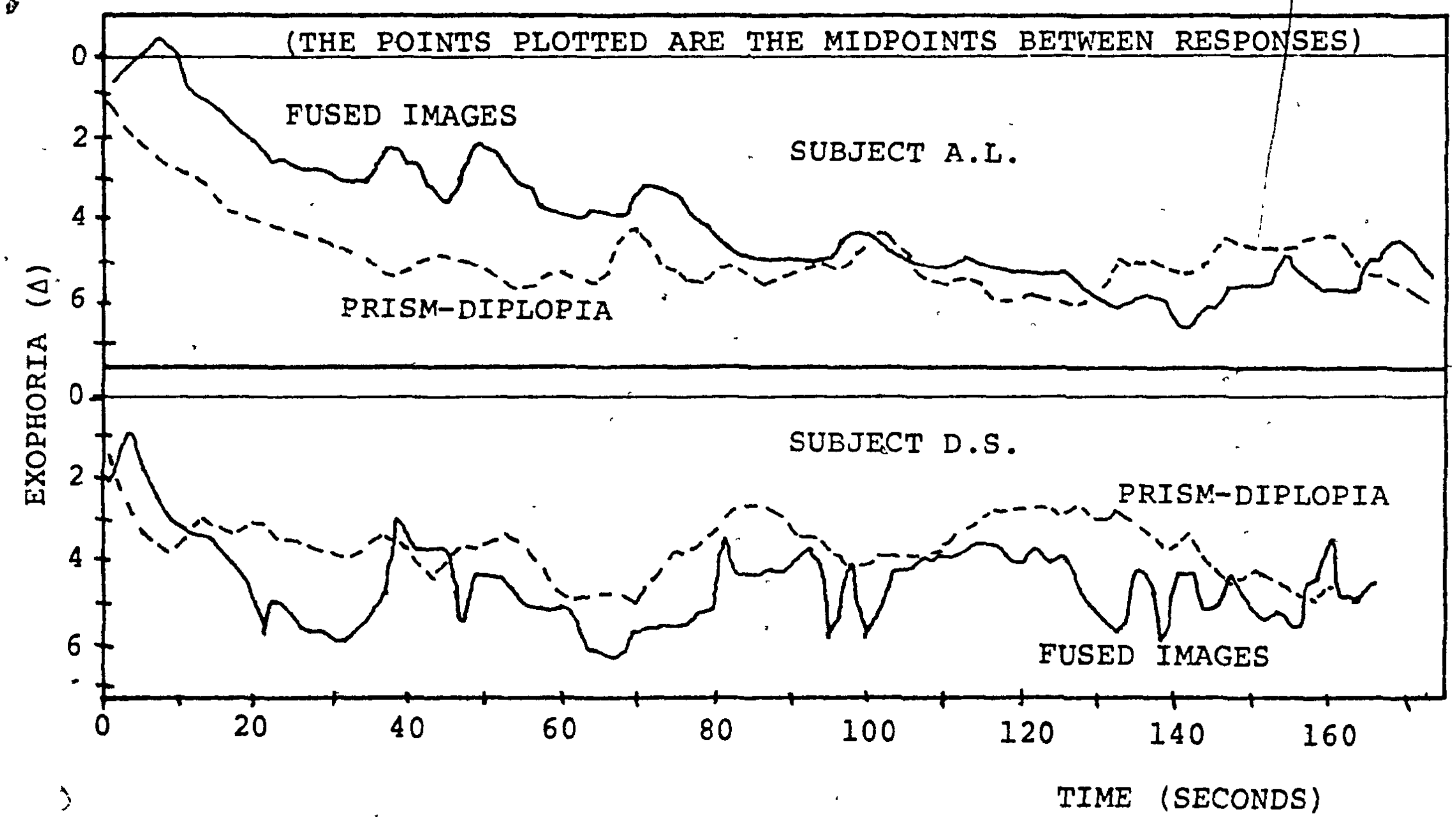

Figure 17. Phoria obtained by the prism-diplopia method compared with that found by the fused-images method. The tests were performed on different days.

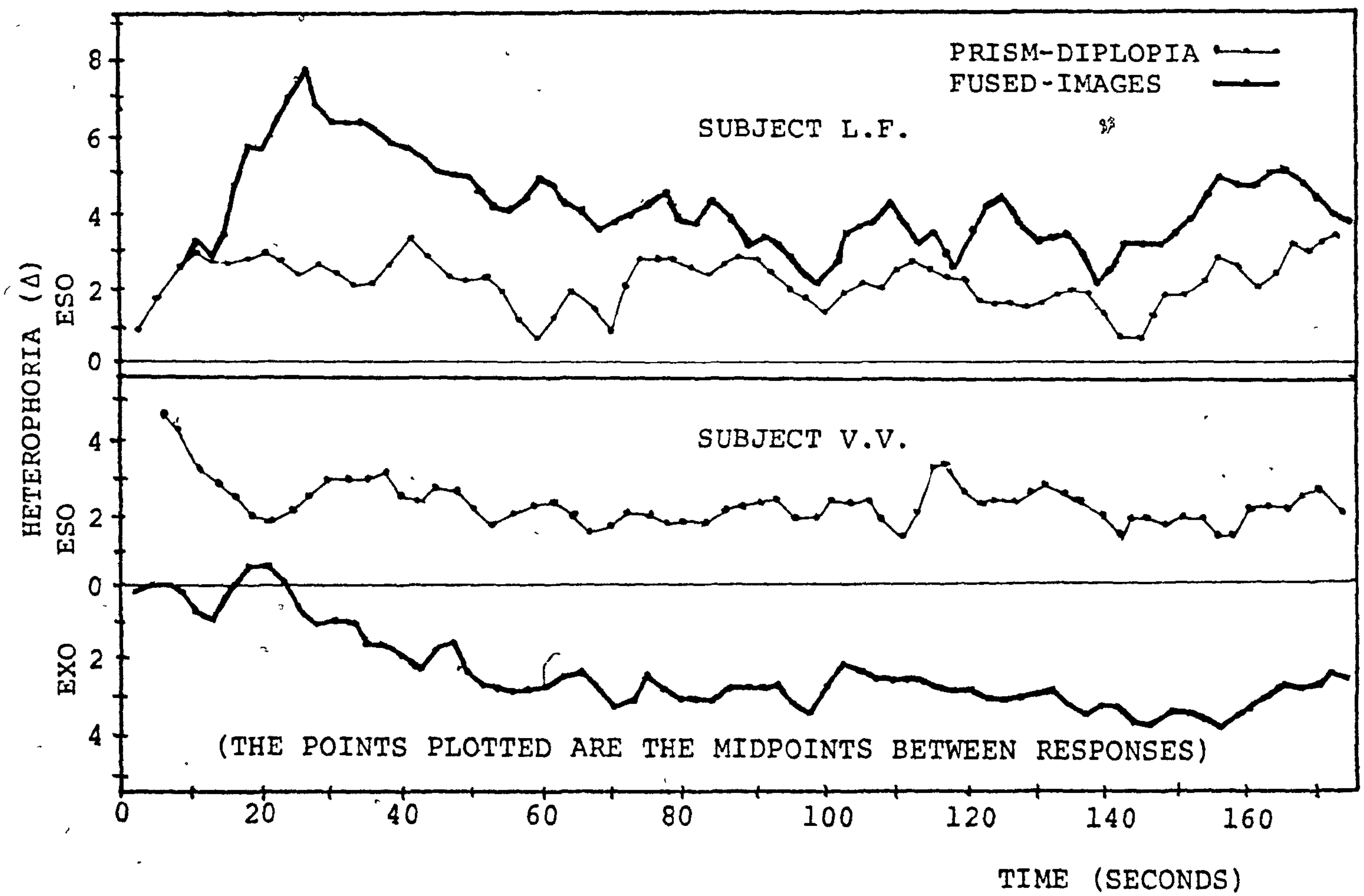

Figure 18. Subjects whose responses to the fused-images method were different to those obtained by the prism-diplopia method. Subject L.F. performed the tests in quick succession..

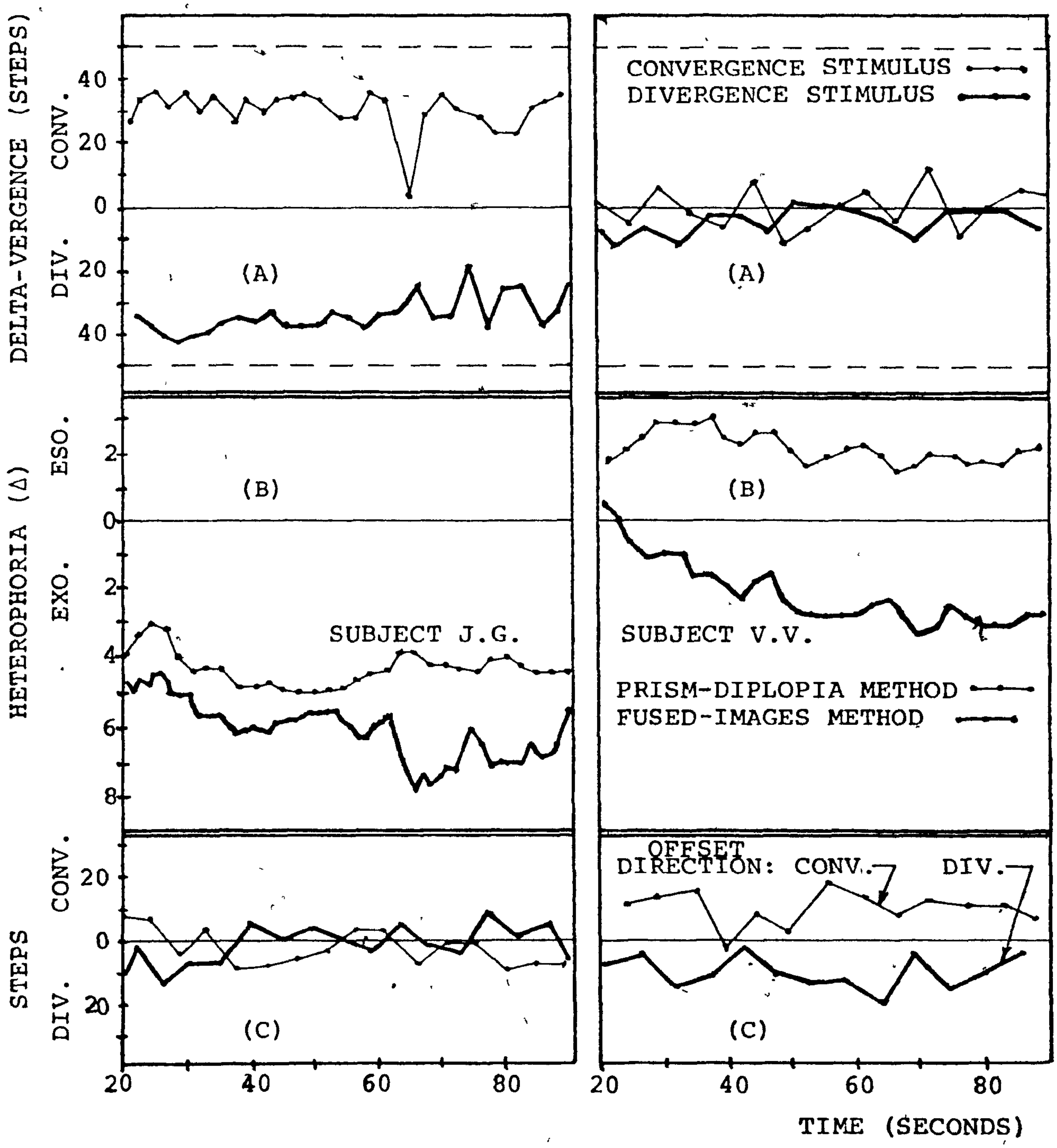

Figure 19. The delta-vergence analysis for the fused-images midpoint plot in (B) is shown in (A). If the same mathematical analysis is applied to the prism-diplopia midpoint plot in (B) the result is as shown in (C).

Dissociated phoria with and without starting offset. The programming of the phorometer enabled a start to be made from some prism value other than zero. It was also possible to remain at this value for a pre-determined time. When the subject started the program by actuating the switch, the amount of the offset required was read from the switch register and the prism was slewed to that value. If a time delay request were also found, the teletypewriter bell was rung to indicate the start of the timed interval and was rung again to indicate its end. The phorometer program began to be executed after the second bell and it continued until terminated by the operator.

The results of an experiment using a starting offset and a time delay of 10 seconds are shown in Figure 20. These indicate that the presence of lateral prism before the eyes can alter the response pattern even though the subject's eyes are dissociated. The implication is that the eyes were not completely dissociated. Two starting offsets were used, 11.6Δ eso and 11.6Δexo. The phoria curves found with these starting conditions are shown along with the curve measured without a starting offset. From an inspection of this figure, it is obvious that looking through a fixed lateral prism can alter the time course and the ultimate value of the phoria. This has great practical significance because during conventional phorometry the prism must be left at a fixed value from time to time.

Not all subjects respond to the presence of lateral prism in the same way. This is illustrated by Figure 21 in which subject V.V., who generally gave steady results and often approximated orthophoria, was obliged to look through a starting offset of 11.6Δ eso for 53 seconds before the test was started. It is remarkable to see that his first

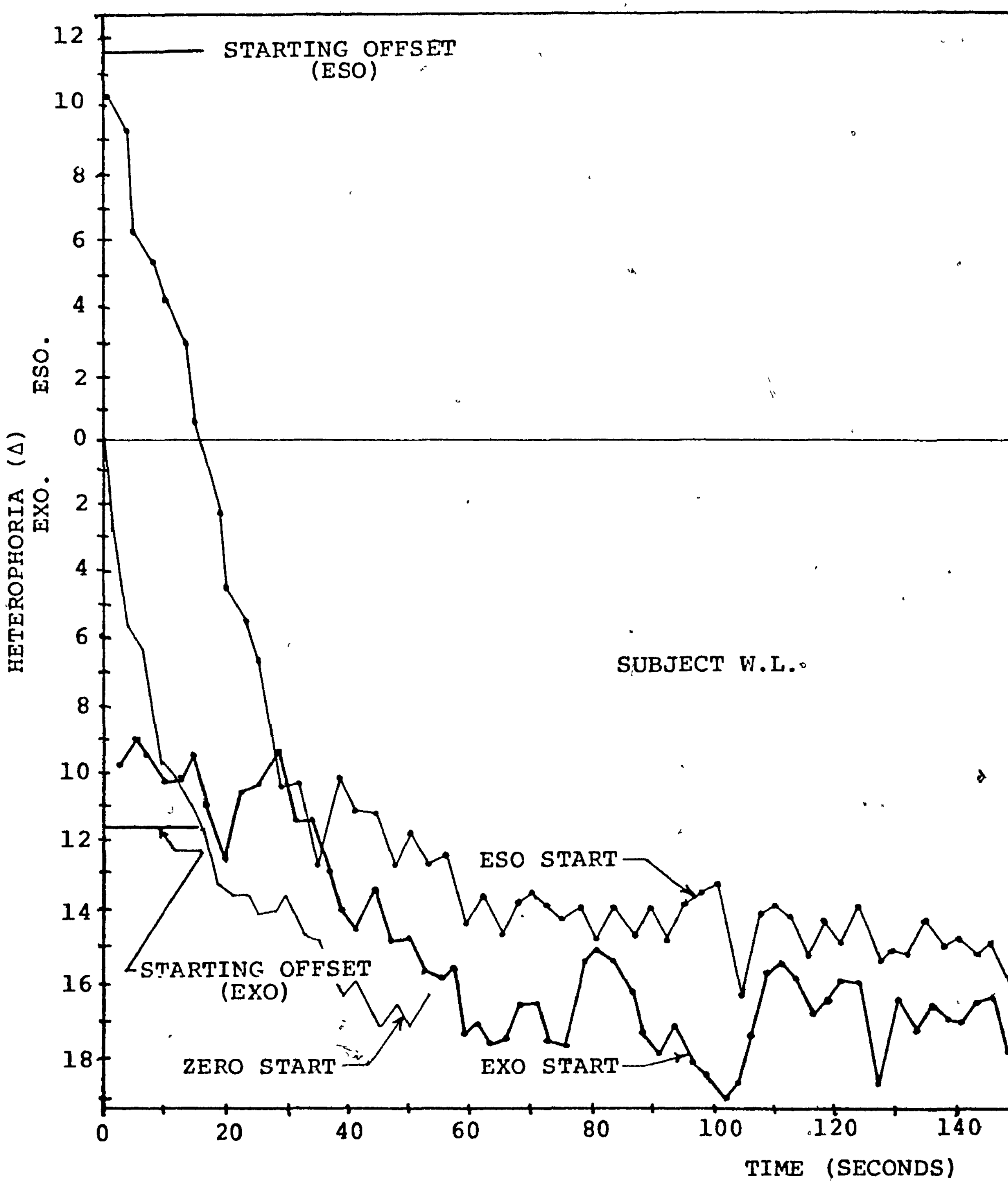

Figure 20. The subject looked through the starting offset prism for 10 seconds before starting the prism-diplopia test. The tests were performed in quick succession.

response was in a direction showing that he had a greater eso deviation than was necessary to align the dissociated images. The test was repeated with the starting offset in the exo direction and the results were a mirror image of those shown in Figure 21. The curve for no starting offset shows that after the initial slewing of the phoria the starting offset had no further effect. It is worth remarking that the subject was unaware of the purpose of this experiment and that no instructions were given that might have made him try to fuse the dissociated images together. After the test he stated, still without prior knowledge, that the images tended to line themselves up but were seen to be continuously moving into and out of alignment.

Cover test. The automatic cover test gives results which are particularly interesting because the cover test is generally considered to be the closest to the ideal. Results for 3 subjects are seen in Figure 22. Subject C.P.'s results are for tests repeated with a minimum of delay whereas those for V.V. were separated by an interval of 7 days.

A comparison of the three curves shown for subject J.F. brings out an interesting point. The fused-images test gives results closer to the cover test than does the prism-diplopia method.

The results shown in Figure 22 were obtained using a 6Δ dissociating prism but it is also possible to perform the test without this device. Comparative results for two subjects are shown in Figure 23. This figure proves, beyond any doubt, that the cover test does not dissociate the images completely. If this were not so the slope of the phoria curve with and without supplementary dissociation would be the same.

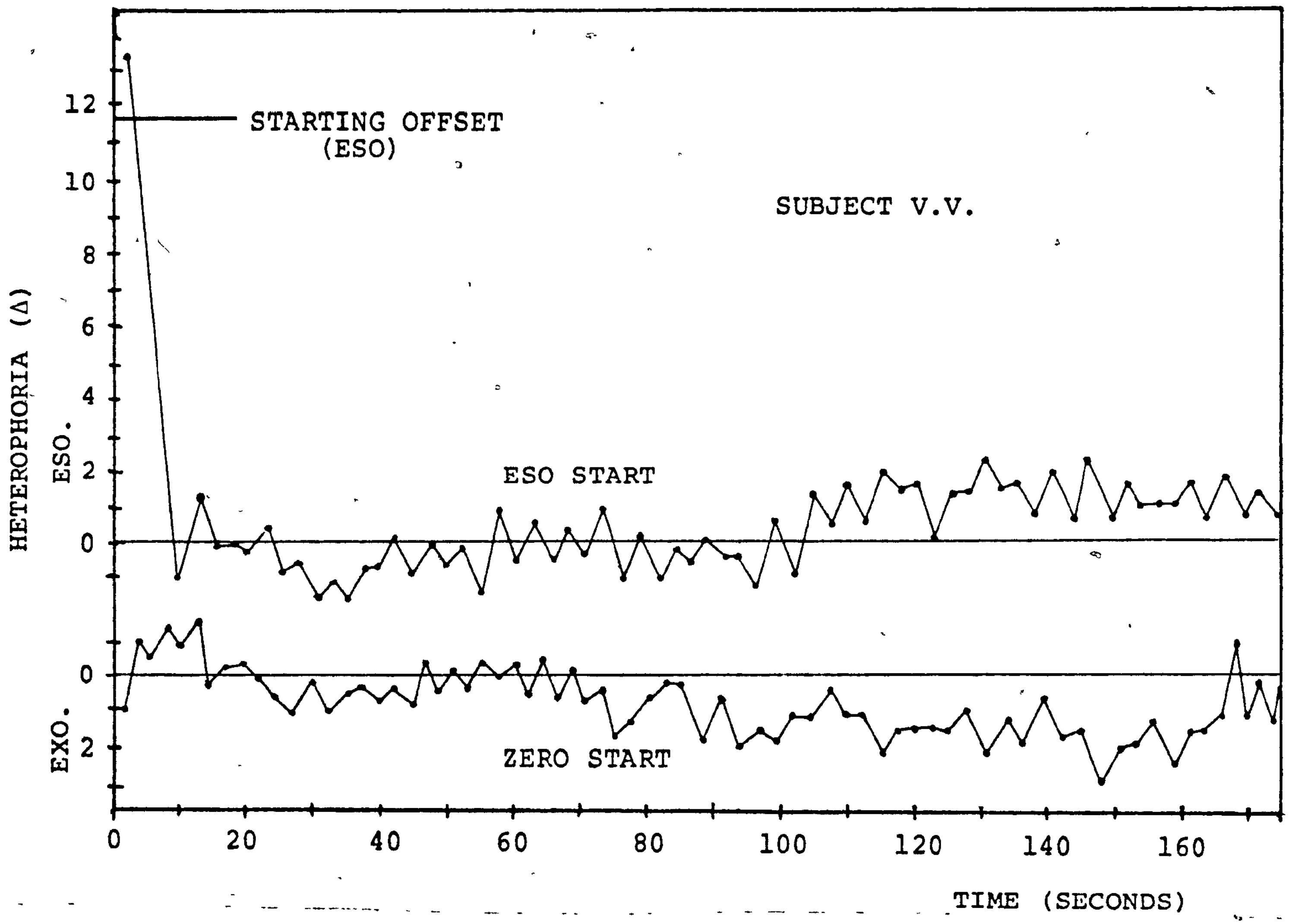

Figure 21. Prism-diplopia results for a subject who in one case, shown by the top curve, was obliged to look through an 11.6Δ lateral prism for 53 seconds before starting the test. The bottom curve shows the results when the subject did not look through the lateral prism before the start of the test.

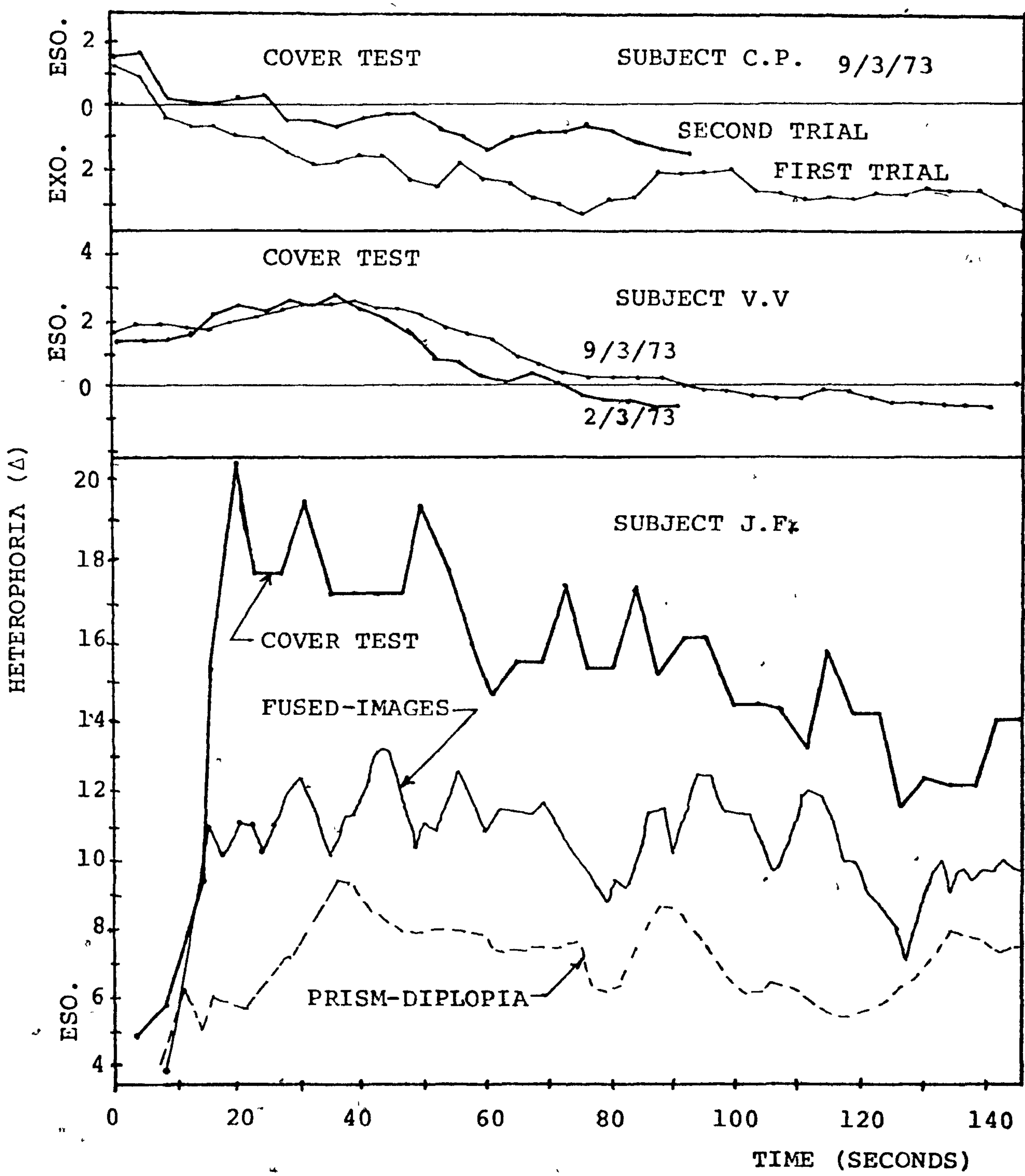

Figure 22. Cover test results shown for 3 subjects. The curves found by two other methods are given for subject J.F. who had a history of strabismus.

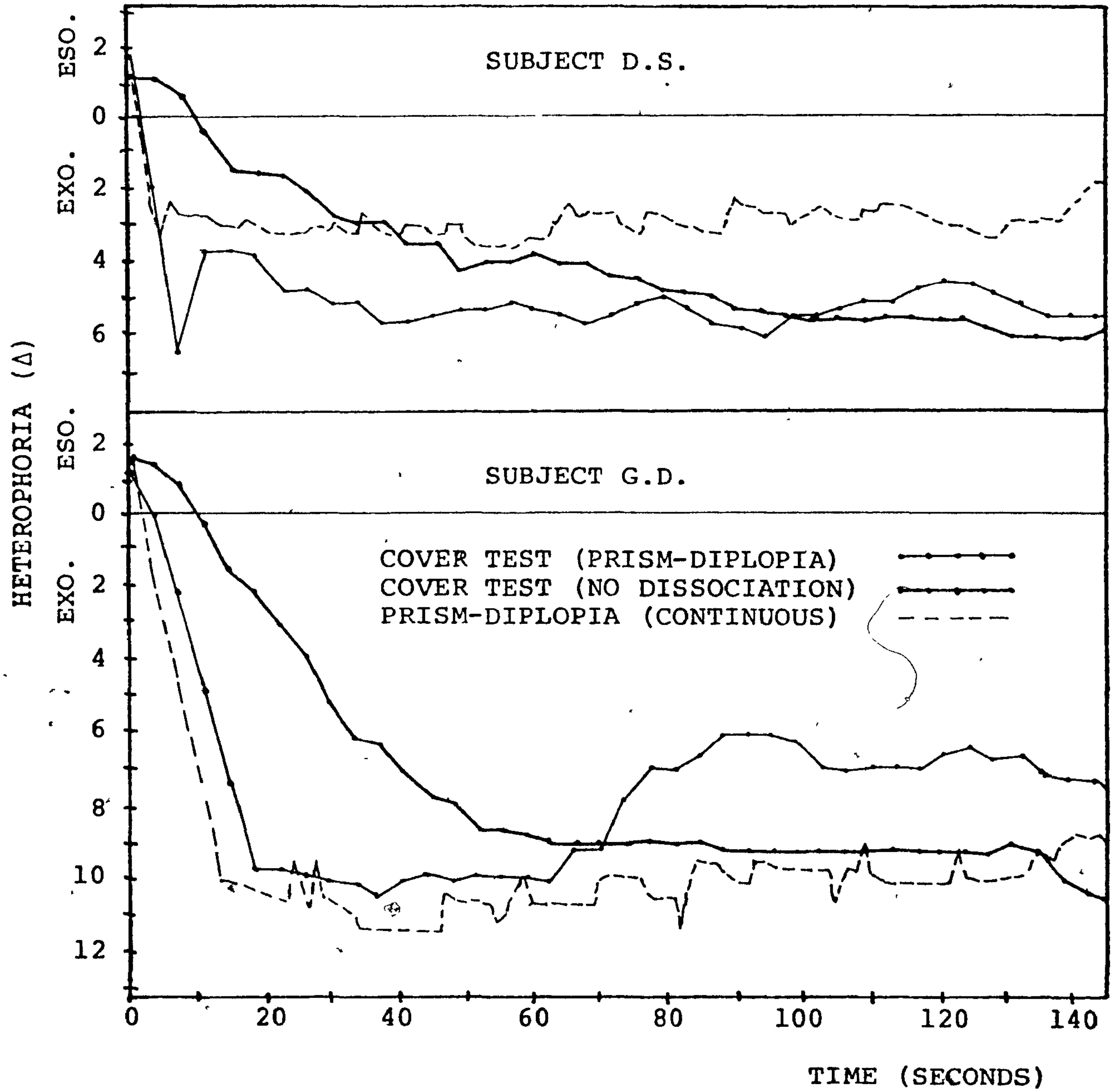

Figure 23. The cover test with prism-diplopia dissociation and with no dissociation. The phoria measured by the prism-diplopia method with continuous adjustment is shown for comparison.

Prism-diplopia test results are also shown in the figure. It is interesting to note that the phoria found by this test is not the same as that found by the cover test. In the case of subject D.S., the prism-diplopia method shows the phoria to be about 2Δ less than that found by the cover test. The prism-diplopia phoria for C.D. is, in general, greater than that found by the cover test. This illustrates the difficulty in determining which test method gives the "true" value of the phoria.

Continuous alignment. If the cover test program is used without the cover screen but with the dissociating device, the test becomes one in which the subject can keep the images in alignment at all times. The cover test program was modified so that the screen was held open throughout the test. The prism's power was recorded at 1 sec intervals. Phoria curves obtained by this method are shown in Figure 24. Two of these have been repeated in Figure 23.

When these results are compared with those obtained by the prism-diplopia method, they are seen to be much less variable. As an example of this compare the curve for W.L. with those shown in Figure 15. The average phoria for this subject is 4Δ less by the continuous alignment method. On the other hand, the results for D.S. are similar by these methods. An interesting response pattern is shown by C.P. because for 40 seconds the same phoria is maintained until, after an eso increase of short duration, the phoria shifts from 2Δ eso to 2Δ exo. This illustrates the value of repeated measurements. Without them, the phoria would have been considered to be stable at 2Δ of esophoria.

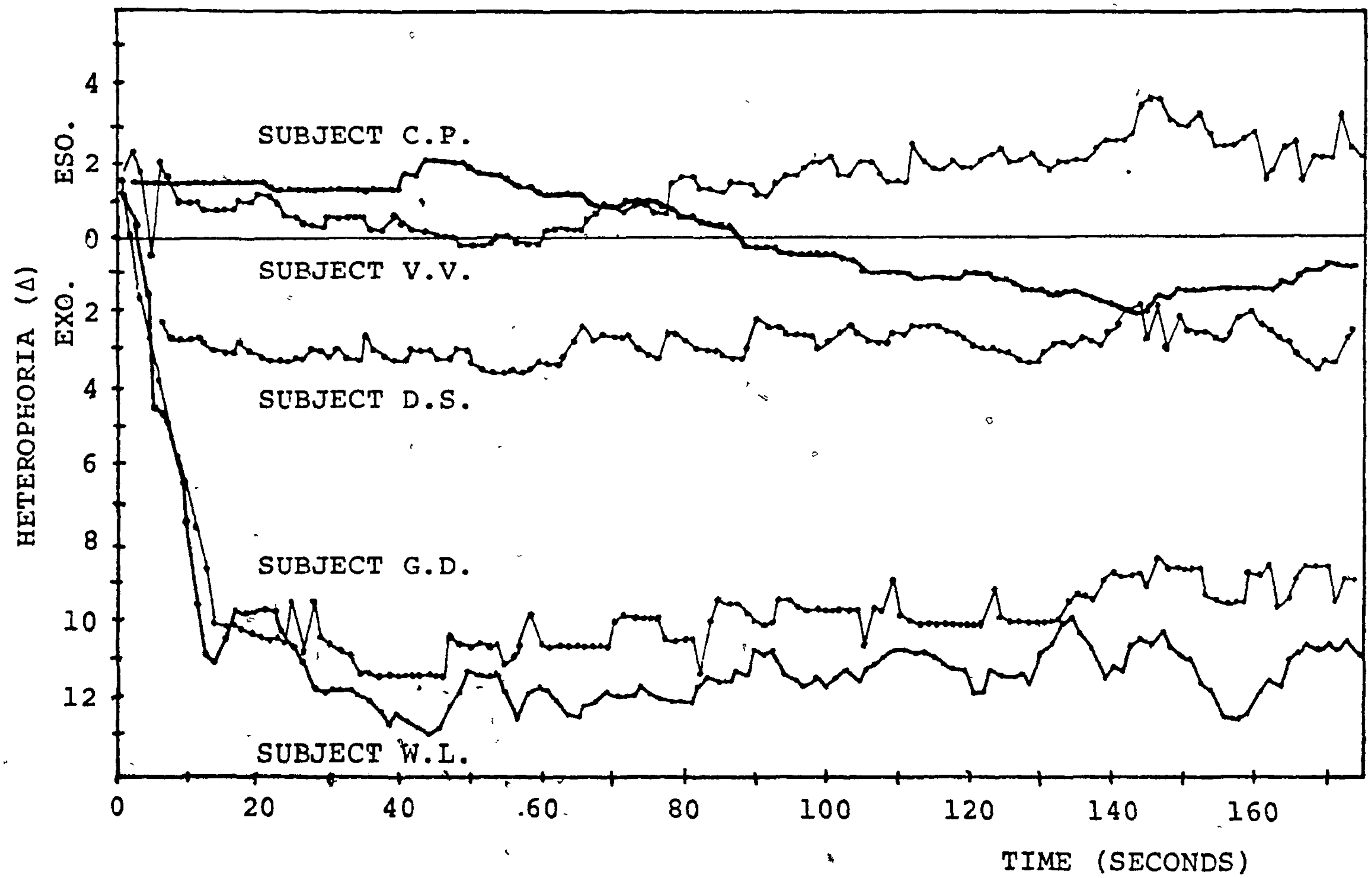

Figure 24. Phoria results in which the subject adjusted the image alignment continuously by means of a potentiometer. Prism-diplopia dissociation was used. The prism's power was recorded every second.

Associated horizontal phoria. Phoria data found by the fixation disparity method is shown in Figure 25. It is interesting to compare the cover test results found in Figure 22 with those in Figure 25. Certain similarities can be found in the results of V.V. and C.P. On the other hand the results already seen for W.L. are quite different to those found in Figure 25. Subject M.A. is remarkable for his consistency and acuteness of judgement regarding the precision of alignment.

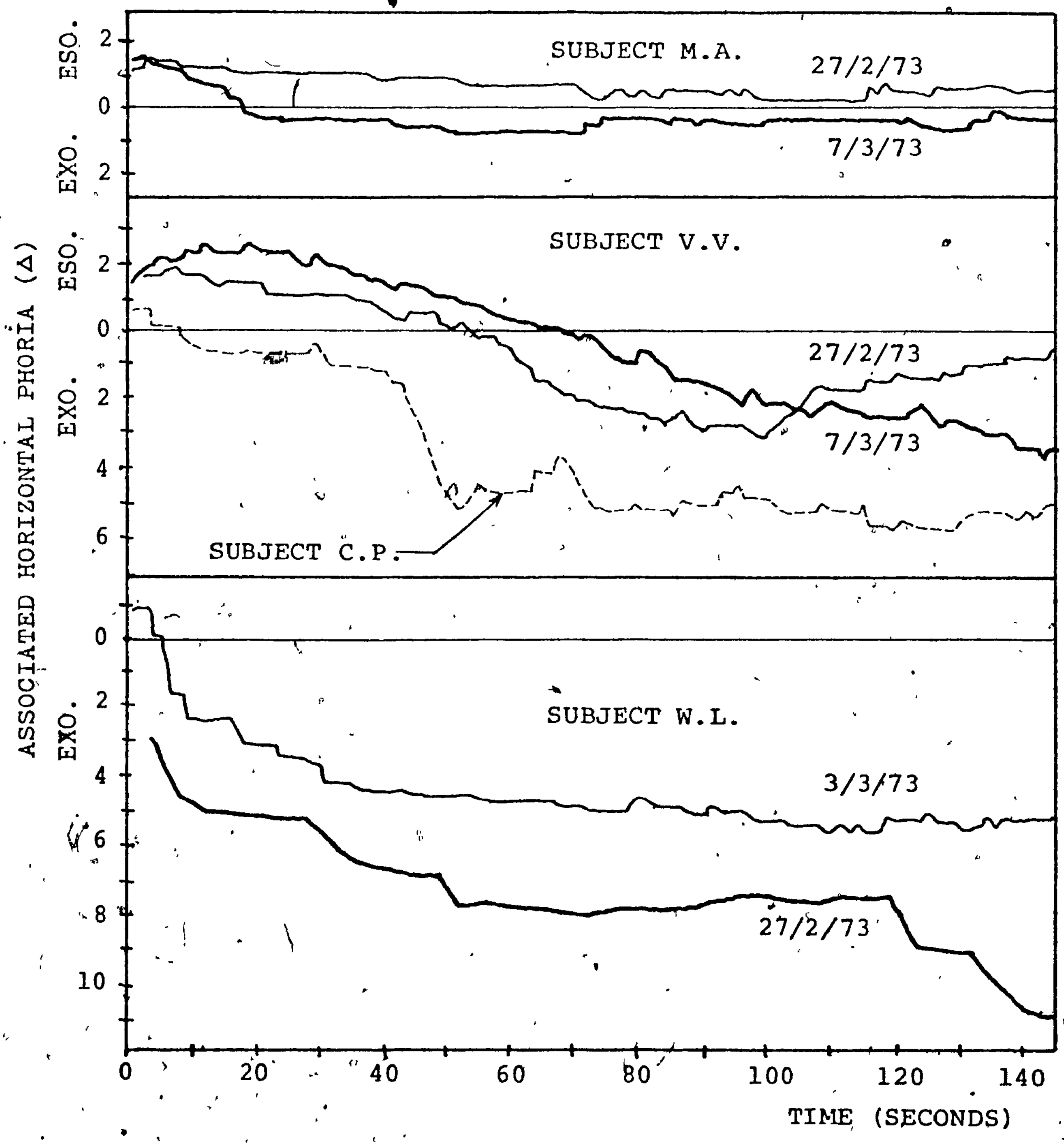

Figure 25. Associated Horizontal Phoria for 4 Subjects.

CHAPTER VI

DISCUSSION

Some discussion of the results has already been made in the preceding chapter. This chapter is devoted to findings of special interest. These include observations on strabismus, dissociation and the effect of accommodation changes on the phoria. Heterophoria is re-defined and new ways to measure it are considered.

I. FINDINGS OF SPECIAL INTEREST

Findings of special interest have been made during this study. These were entirely unforeseen. Those singled out for presentation here have some clinical significance.

Strabismus. Purely by chance, two subjects were tested who had a history of strabismus dating from their childhood. Both subjects were in their early twenties. The phoria results for these subjects were so different from the rest that it prompted an enquiry into their visual history. When it was found that they were prone to strabismus, they became the object of a special study. One of the subjects, J.L. had undergone an operation for the correction of convergent strabismus, while the other, J.F., had never been treated surgically.

The phoria measurements for subject J.F. are shown in Figure 26. The delta-vergence analysis of this data is found in Figure 27. The upper part of Figure 27, marked TRUE DELTA-VERGENCE, shows the delta-vergence analysis applied to the fused-images data. Comparing this with Figure 19, parts A, it seems that J.F.'s responses are unusually variable.

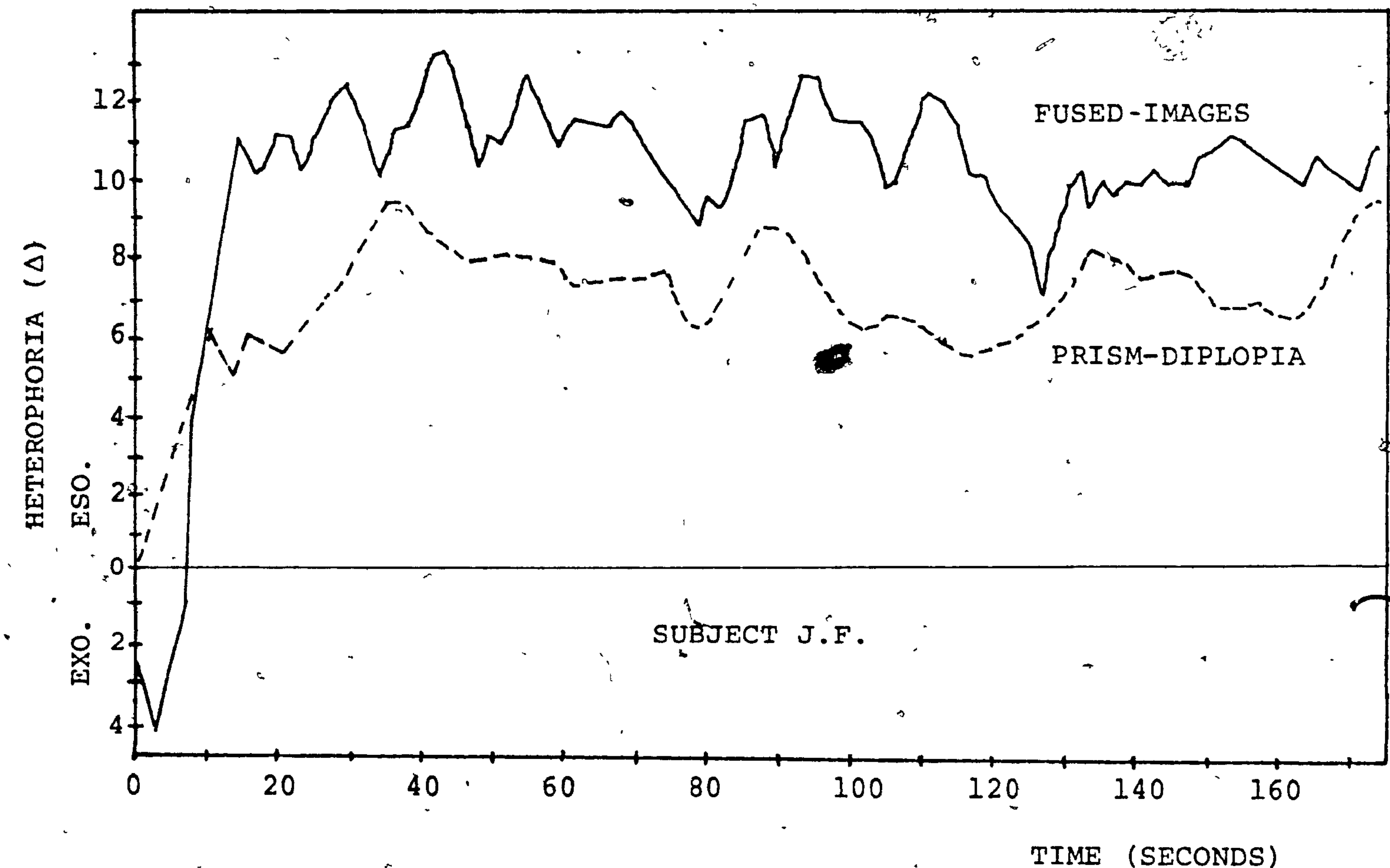

Figure 26. Phoria found by the prism-diplopia method and the fused-images method. The subject had a history of convergent strabismus. Midpoints plots are shown in both cases.

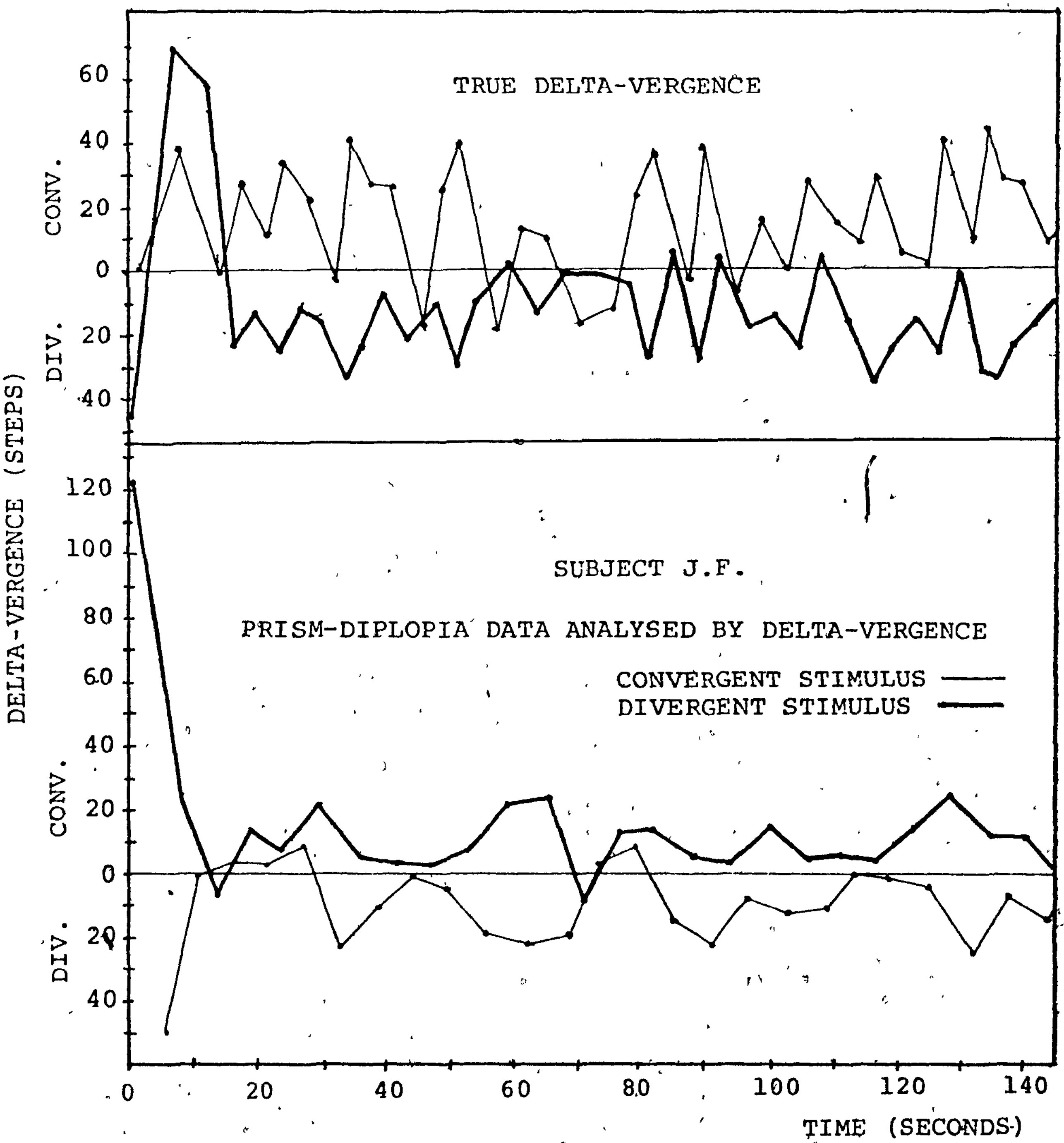

Figure 27. Delta-vergence analysis applied to the data presented in Figure 26.

The lower graph in Figure 27 is an analysis of the prism-diplopia data by means of the delta-vergence procedure. The results of this analysis are not, of course, based on the same test conditions as those shown in the upper graph. The interpretation of the results of the analysis is not as simple as in the case of the fused-images data. A subject whose phoria was steady and who made no errors in his response to alignment would have two delta-vergence curves, one on each side of the zero line. The curves would not fall on that line because of the subject's reaction time. If the curves were not straight lines it could be because there were variations in the subject's estimation of the moment of alignment. If the phoria were to vary between measurements, this would be reflected in variations in the curves. Another possibility is that the test conditions stimulated the subject to make a change in vergence even though he was dissociated. In J.F.'S case, the curves are somewhat different to those already shown in Figure 19, parts C. In particular, it should be noted that a divergent stimulus results in a convergent posture of the eyes and vice versa.

The data of J.L. has been treated in the same way as that of J.F. and the results are shown in Figures 28 and 29. The delta-vergence analysis applied to the fused-images data gives a picture of a remarkable vergence system. When this analysis is applied to the prism-diplopia data, the results are not unlike those of J.F. but are more extreme.

The results shown in Figure 29 deserve special comment because the subject behaves as if a stimulus for convergence results in divergence and vice versa. Since this interpretation will undoubtedly be questioned, the original data and graph are given in Appendix G. A prism position plot is included

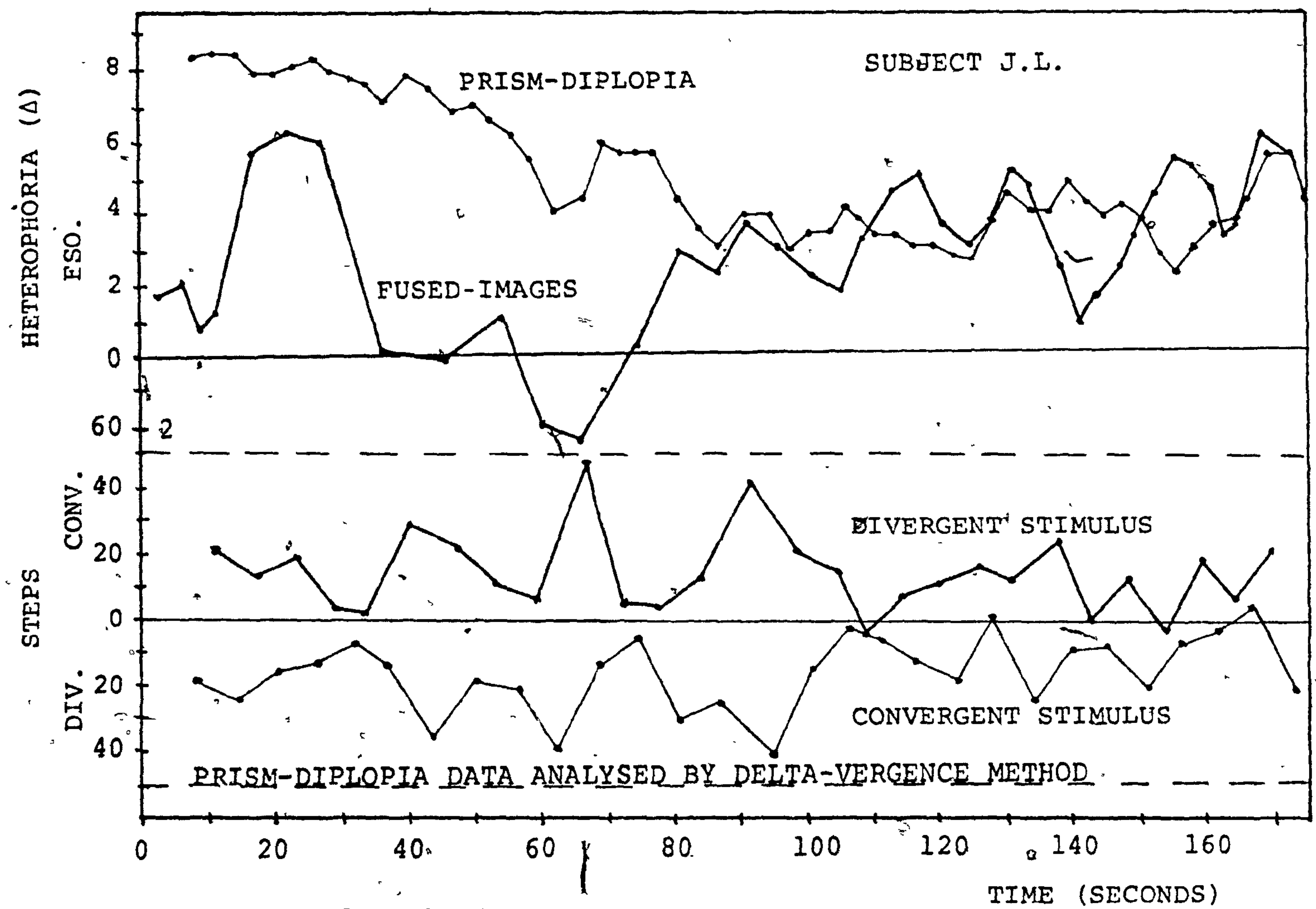

Figure 28. The upper curves show phoria results for a subject with a history of strabismus. The lower curves show the results of the delta-vergence analysis applied to the prism-diplopia data.

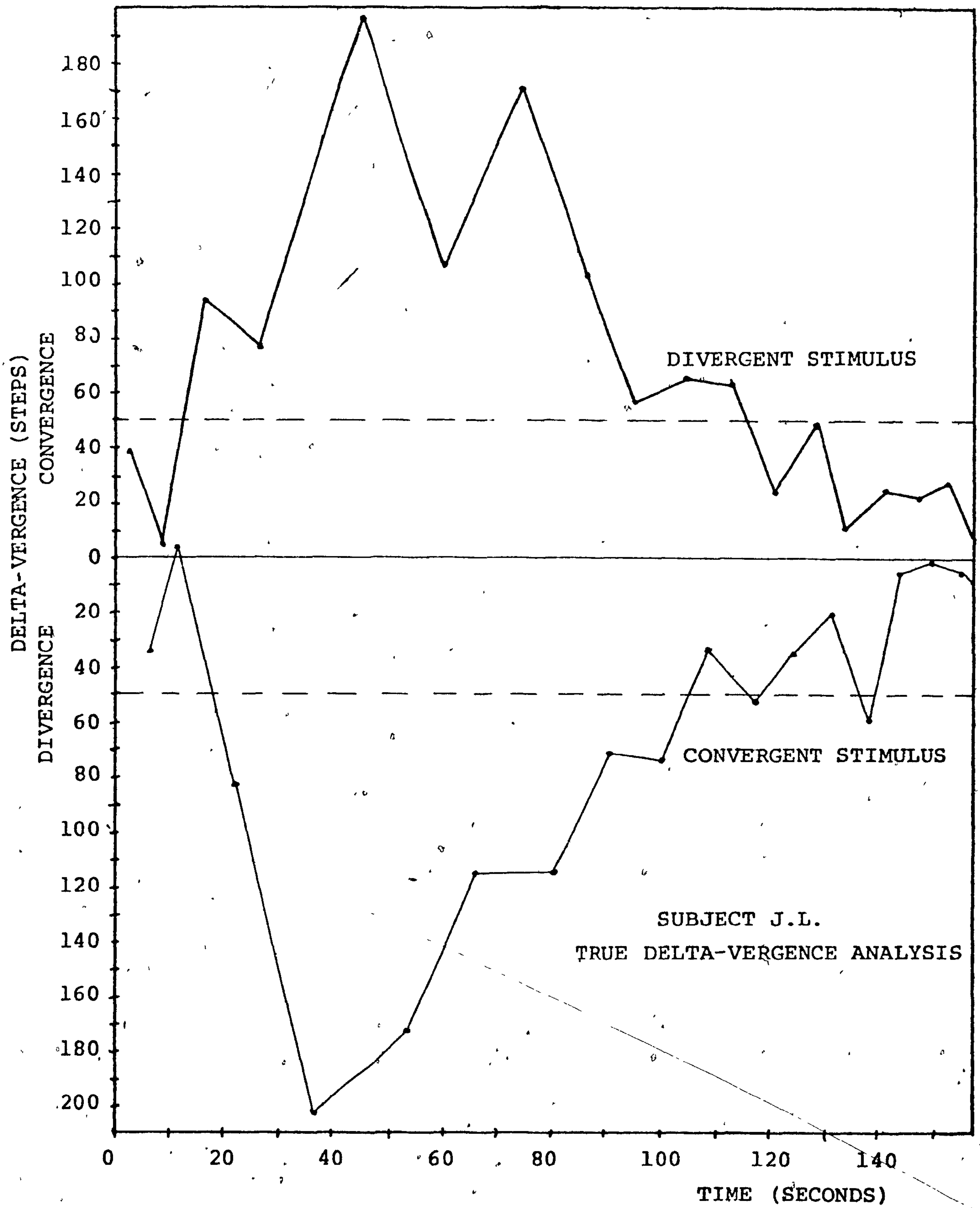

Figure 29. Delta-vergence analysis of the fused-images data presented in Figure 28.

to prove that the results are not due to an error of interpretation. Another check on the validity of the data is that it is impossible for the responses to pass the amount of the offset jump. This can only appear to happen if the offset jump limit on the other side of the zero line is crossed. If the subject were to converge by more than the amount of the offset jump, he would be on the wrong side of the subsequent vergence change and the prism change would make him even more out of alignment. It is also unlikely that his vergence could change with such a speed that he could be converged by more than the offset jump. The prism-diplopia data, when analysed by the delta-vergence procedure, shows that the subject diverges when a stimulus to converge is presented. This serves to confirm the analysis of the results. The contradictory responses are less extreme but this may be due to dissociation reducing the response to the stimulus.

Figure 30 shows some additional test results for these two subjects. The upper graph shows the fixation disparity test results for J.F. while the lower shows both disparity and cover test results for J.L. It is interesting to note that these results are more often than not on the exophoria side of the graph. This is opposite to the results obtained by the fused-images and prism-diplopia methods.

The results for J.L. show two unusual features: (1) at the start of the fixation disparity test, the subject was in a state of diplopia for 18 sec and (2) during the first 40 sec of the cover test the images were seen in perfect vertical alignment. These responses were quite abnormal. When the cover test results were seen to be constant the operator altered the potentiometer setting as can be seen in the figure.

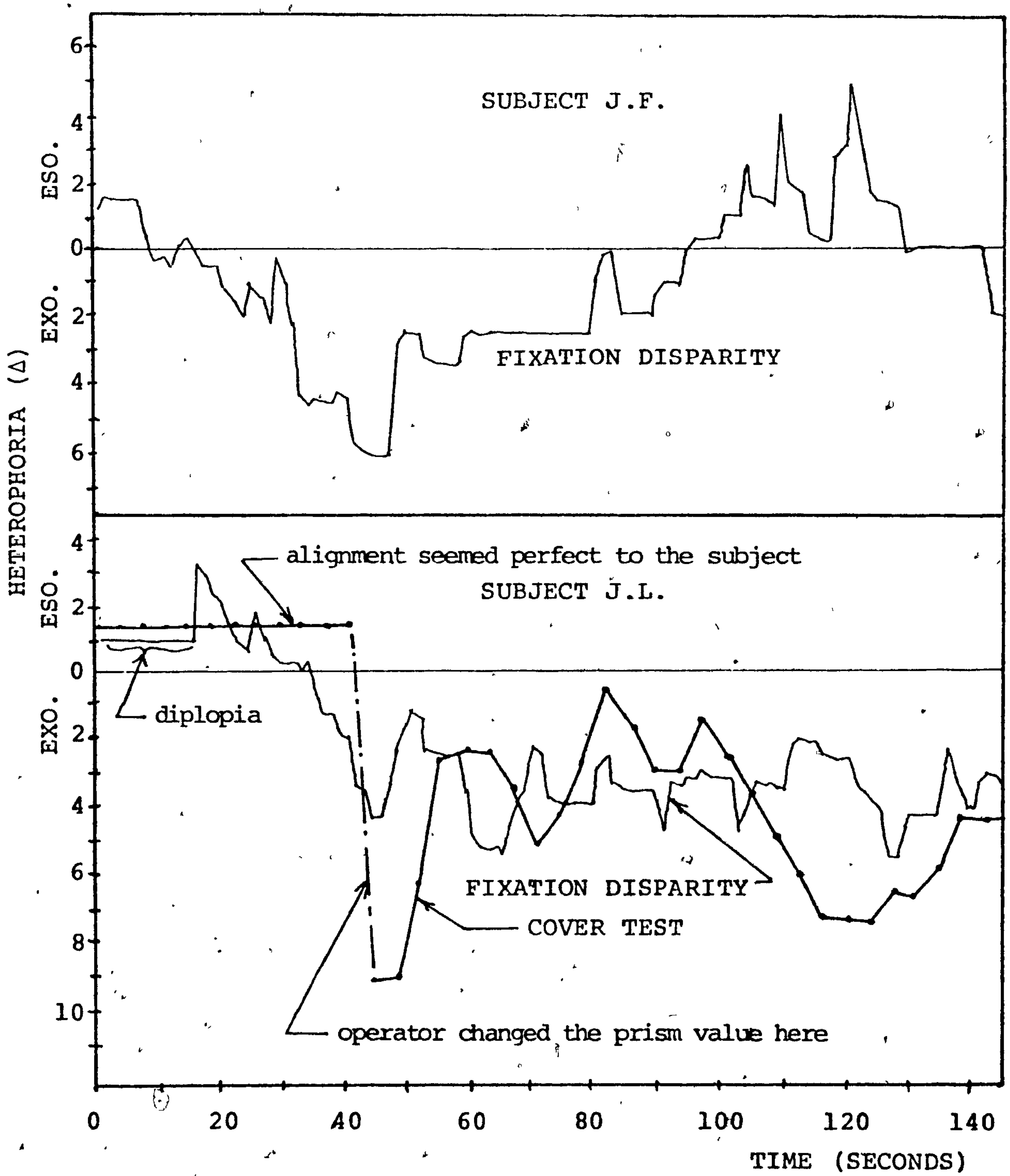

Figure 30. Additional data for the subjects of Figures 26 and 28. Fixation disparity for J.F. and fixation disparity and the cover test for subject J.L.

Thereafter, the original phoria value was never repeated and there is every evidence that the subject was capable of judging alignment throughout the test. With regard to the diplopia, it is strange that a test in which all binocular clues are present, with the exception of two vertical lines, should give rise to diplopia, whereas in the cover test, where the intention is to eliminate fusion, the subject's vergence locks itself into a fixed value. After the cover test, the subject was asked if both images were seen during the first 40 seconds and the answer was yes. Therefore, the results cannot be said to be due to suppression.

Dissociation. The results of this study show aspects of dissociation which are of great practical importance in phorometry. Three observations about dissociation can be made. These are:

1. The phoria response pattern elicited from the subject by different test methods differs from subject to subject.

2. The amount of lateral prism which the subject looks through may influence the value of the phoria and its time course.

3. The way in which the subject looks at the dissociated images during the test may alter the phoria.

The proof of the first observation is to be found in Figure 31 in which a variety of phoria tests have been performed by two subjects. Four different test methods are shown for C.P. and 5 for M.A. Among the subjects tested C.P. was found to give consistent phoria values of approximately the same magnitude. On the other hand M.A. had dissimilar response patterns for each method. Tests common to both subjects were the associated phoria, the cover test with prism-diplopia dissociation and the Maddox-rod test in the dark using continuous alignment. The Maddox-rod test with the room lights

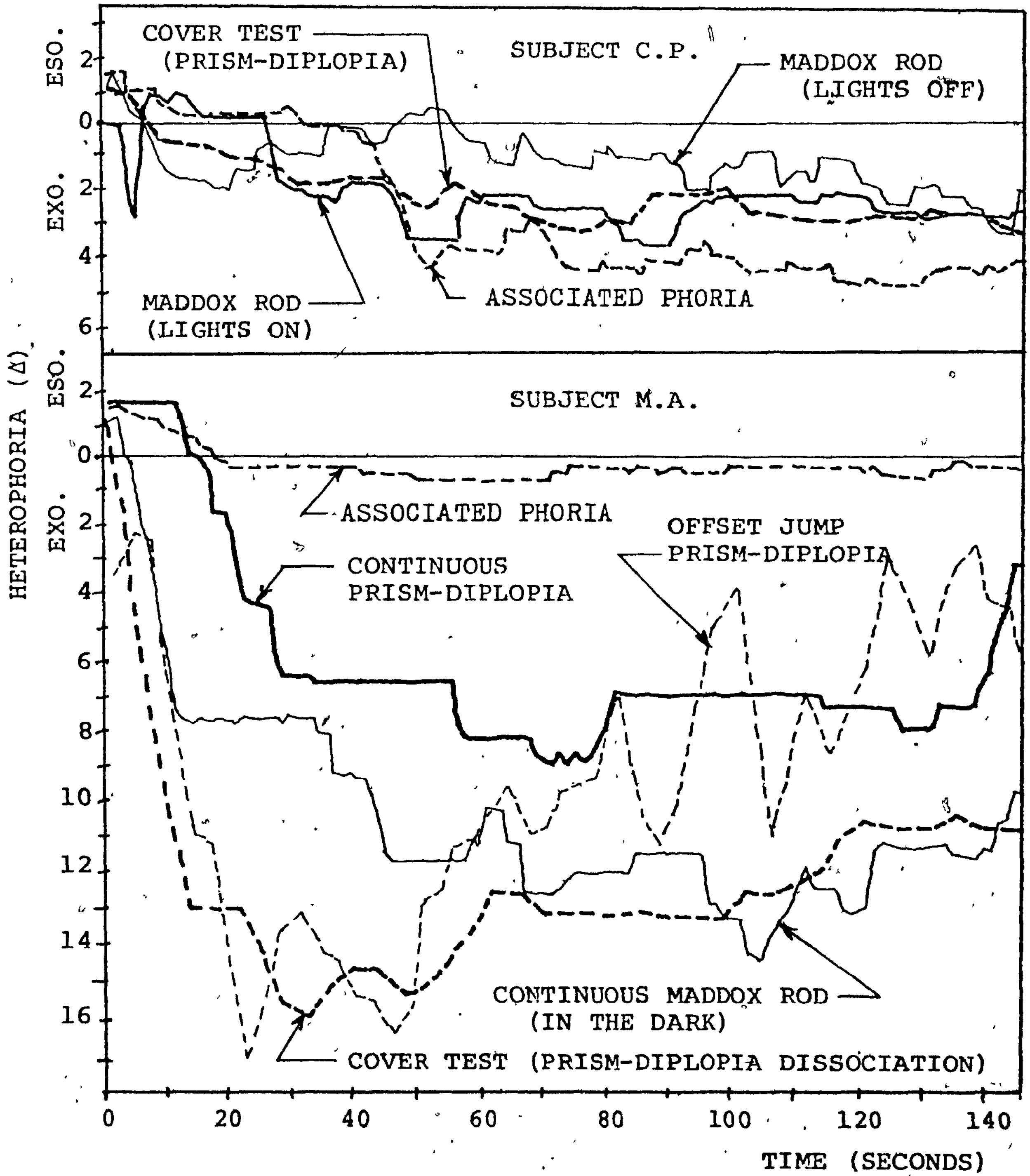

Figure 31. Phoria results obtained by different means of dissociation as well as by fixation disparity.

on was performed by C.P. but M.A. could not do this because he could not see the vertical line of light through the Maddox-rod. Two other methods are shown for M.A. These are the prism-diplopia test using the offset jump and the same test using continuous alignment.

A comparison of the results for these two subjects shows that the response pattern elicited by a particular means of dissociation and test procedure is a characteristic of the subject and not necessarily of the test. It is also clear that a test that gives a minimum phoria for one subject may give a maximum for another. The Maddox-rod test performed with the lights off illustrates this as does the associated phoria.

The results for subject M.A., shown in Figure 31, are enough to discourage anyone from making generalizations on the merits of the different methods of dissociation. This subject claimed to have "funny eyes" and compared to C.P. his evaluation would seem to be correct. His most striking characteristic was the ability to perform the associated phoria test with great precision. This can be seen by the fine adjustments that he has made during the course of the test. Three curves are shown for tests in which a vertical dissociating prism was used. Of these, the most erratic is that of the original prism-diplopia method. At first glance, one might say that this showed the offset jump to be an undesirable feature, but if one looks at the cover test results it is found that both curves are similar for the first 50 seconds and show the same general trend thereafter. Since the cover test is often considered to be the "ideal" this speaks favourably for the prism-diplopia method. When the prism-diplopia dissociation is used, but the adjustment is made continuously the phoria curve is quite unlike that of the cover test. This serves as additional proof of the second observation made above. The retention of the starting phoria for 12 seconds and other features suggest that association occurred even though the images were dissociated. That the offset jump can serve to disrupt the association of the images is obvious when the offset jump and the continuous adjustment curves are compared.

Regarding the second observation on dissociation, that the amount of lateral prism which the subject looks through may influence the value of the phoria and its time course, both Figure 20 and 21 show this to be true. When the alignment of the images is adjusted continuously, the same condition arises because there is no offset jump to alter the relative position of the images. When adjustment has been made continuously, as is shown in Figure 24, the phoria curves are seen to be much more continuous than those found by methods that alter the prism after each response. Subject C.P.'s curve is a good example of this. W.L.'s curve in Figure 24 should be compared with those in Figure 15. In this case, continuous adjustment has decreased the amount of exophoria by about 4Δ.

The third observation was that the way in which the subject looked at the dissociated images during the test could alter the phoria. This variable in the dissociation of the eyes is demonstrated in Figures 32 and 33. Here the subject, the author, deliberately changed his method of looking at the dissociated images from test to test. The result of such an experiment, with dissociation by a Maddox-rod, is shown in Figure 32. Four ways of looking at the images were employed. These were:

1. To always look at the point of light and to avoid, as much as possible, looking at the image seen through the Maddox-rod.

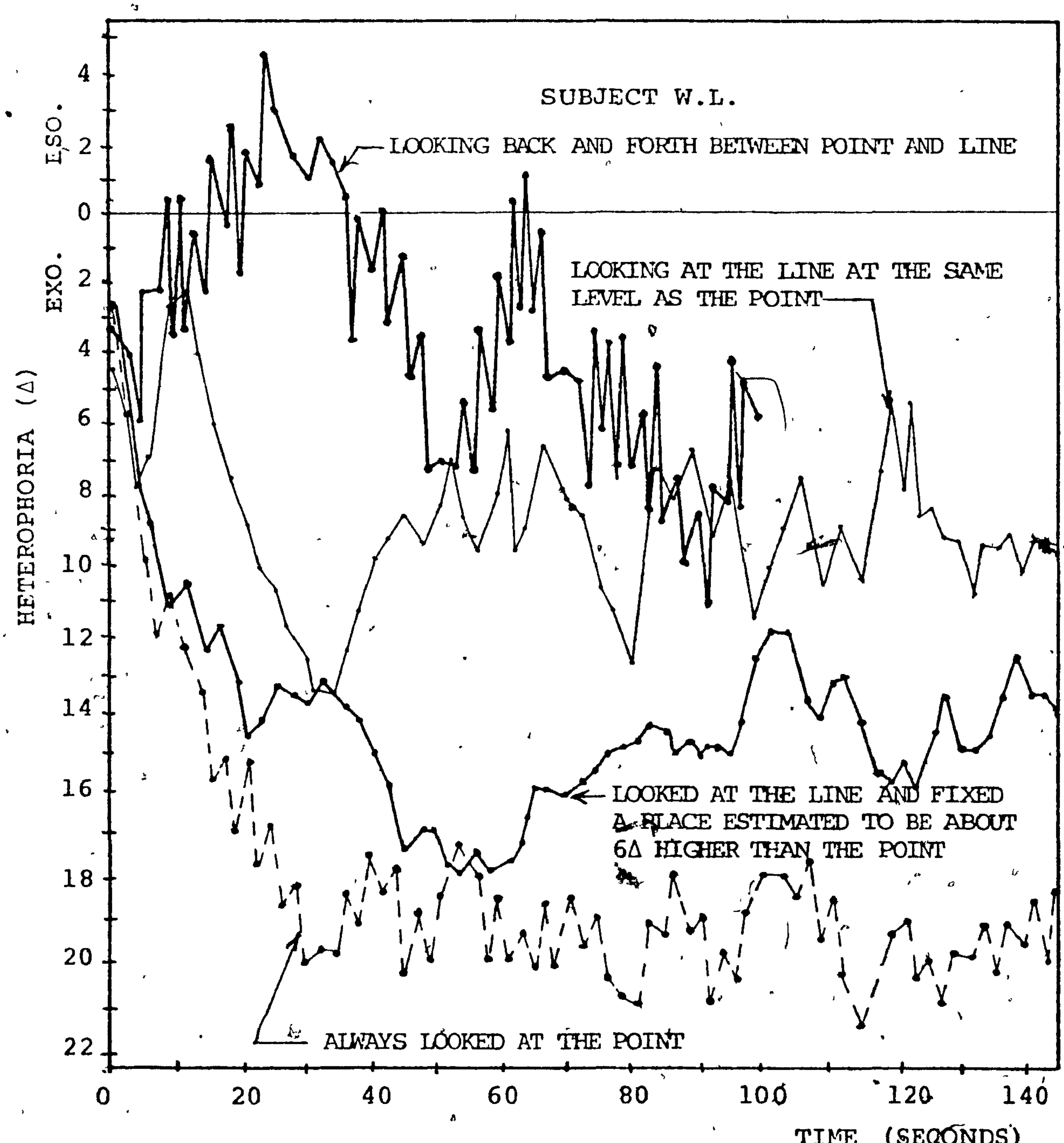

Figure 32. Four different phoria measurements for the same subject showing that the value of the phoria can be altered by a change in the fixation pattern on the part of the subject. Dissociation was by Maddox rod using the prism-diplopia program.

2. Always look at the line of light, seen through the Maddox-rod, and look at it at the same level as the point of light seen by the other eye.

3. Look back and forth between the point image and the line image.

4. Look at the line image but at a position estimated to be about 6Δ higher than the level of the point image.

The fourth procedure was intended to simulate a 6Δ dissociating prism. The curve for this procedure was the closest to that obtained when the point was regarded directly. On the other hand, looking back and forth between the images caused an eso shift in the phoria. When the 5Δ of esophoria, obtained by this method, is compared with the 20Δ of exophoria found when the point was fixed, there is no doubt that the way of looking at the images may influence the phoria.

A similar procedure was used with prism-diplopia dissociation. The ways of looking at the images were somewhat different and were:

1. To always look at the image seen by the eye not looking through the dissociating device.

2. To always look midway between the images.

3. To look back and forth between the two images.

In the second case, a mental line had to be drawn between the images and its estimated midpoint fixed. The results for these procedures are shown in Figure 33. Once again the third observation is substantiated.

Phoria and accommodation. The synergy between accommodation and vergence is often used as an indirect way of determining the relative influence of accommodation on the position of a fully occluded eye. This is used to establish the AC/A ratio.

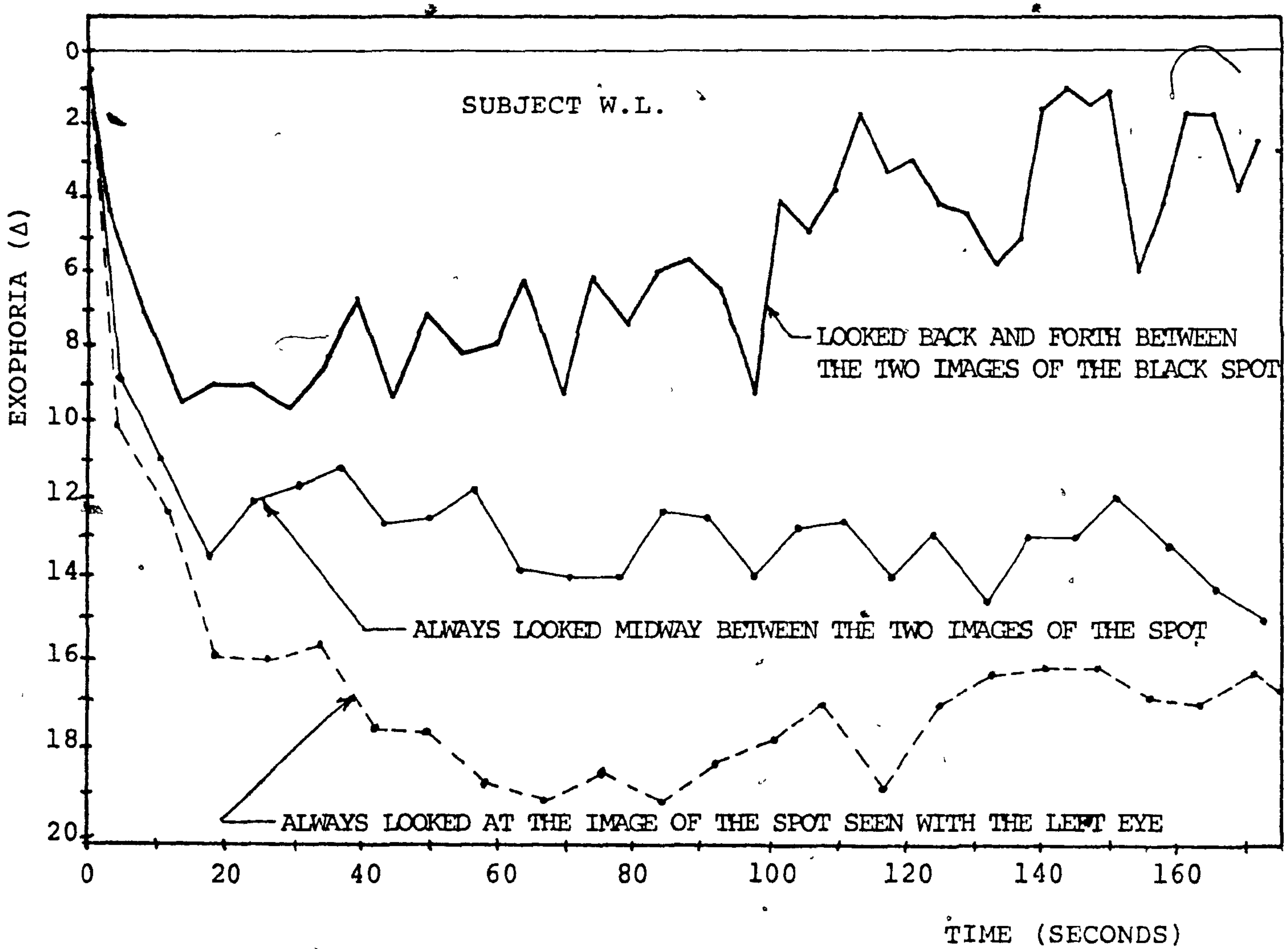

Figure 33. Three phoria measurements for the same subject. Each curve represents the effect on the phoria of a different fixation procedure. The program returned the prism to zero after each response. Prism-diplopia dissociation was used.

Figure 34 shows what happens when the subject is suddenly obliged to change his accommodation. The lens drop phorometer was used and -1.0 diopter lenses were dropped simultaneously before each of the subject's eyes during the sequential measurement of the phoria. The fused-images method had to be used because the holder normally reserved for the dissociating device was used to hold the lens before the right eye. Since this was a pilot study, there was no provision for the synchronization of the lens drop from test to test. The exact moment of the drop was not determined but it was approximately as indicated by the arrows in the figure.

If the curves to the left of the arrows are examined, it is found that the more the subject is obliged to accommodate the less exophoric he becomes. This is the normal synergy between accommodation and vergence. The AC/A ratio for this subject appears to be about 7 prism diopters per diopter. The bottom curve does not show this fully because the subject was undercorrected.

It is not too surprising to find that the phoria curves continue to change after the transient caused by the lens drop. On the other hand, it was unforeseen that the curves for a given dioptric power would appear as continuations of each other before and after the drop. It appears as it the phoria change caused by the drop serves to reset the phoria to correspond to the time course of change that would have occurred had the new lens value been present at the start.

The curves for V.V. are included to show that not everyone shows a decrease in phoria when the lenses are dropped. In the upper curve, the subject shows little change in his phoria after the drop. When lenses have been added to make

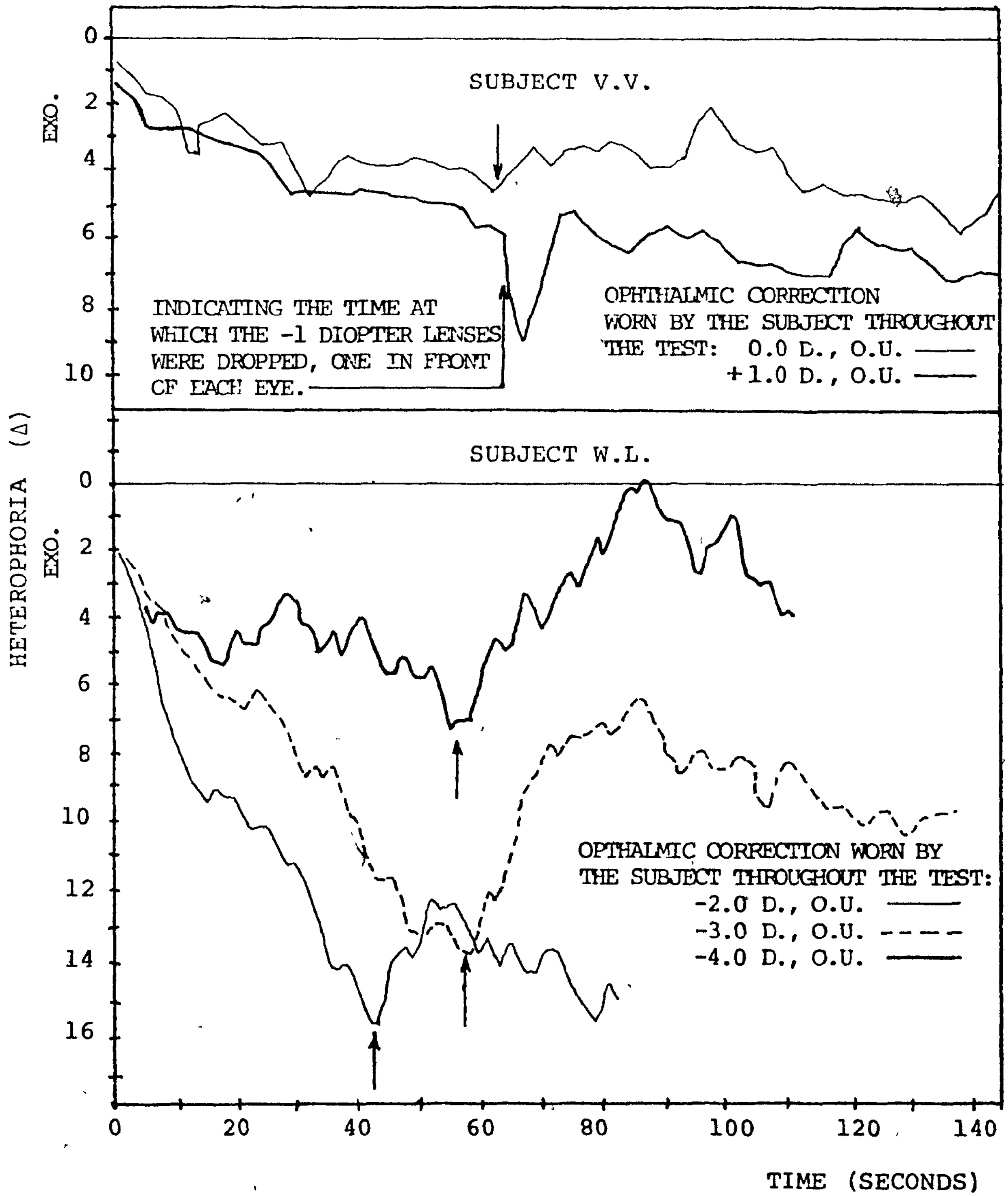

Figure 34. An attempt at determining the AC/A ratio by the phoria gradient method. The fused-images method was used along with a -1.0 D., O.U. lens drop at the time indicated by the arrow.

the subject myopic by 1.0 diopter, the lens drop causes a phoria change in the direction of exophoria. This is the opposite direction to that predicted from knowledge of the synergy between accommodation and vergence. This change proves to be a transient. Such a response would have been missed by conventional test methods.

These results provide evidence to suggest that the lens drop test has a potential for diagnosis in addition to the determination of the AC/A ratio. This topic deserves more study.

II. HETEROPHORIA

In providing us with a new look at heterophoria and its measurement, this study has uncovered many problems and offered little in the way of solutions. This is because it was, in essence, a pilot study in automated phorometry. The original intention was to provide a sophisticated phorometer for research studies and this goal was achieved. Some new thoughts on heterophoria and its measurement were inevitable after such a study and these are offered in the hope that they may be of use.

Defining heterophoria. The various definitions of heterophoria already given or implied often include assumptions which cannot stand up to close examination. Terms such as "position of rest" or "latent squint" are used without justification. The following definition of heterophoria is offered as an improvement on its predecessors:

Heterophoria is defined as the change in vergence which occurs when artificial means render the need for fusion inoperative. Lateral heterophoria is the heterophoria measured in the plane of regard when it is in its primary position.

Although the prefixes eso and exo have a certain value gained through usage it would be better to replace them with mathematical signs. This is almost certain to happen in any event because of the use of computing equipment. An increase in vergence should be indicated by a positive sign because this convention is already in use.

While the definition of heterophoria states that the need for fusion must be inoperative, this study has shown that there is some stimulus to fusion in most, if not all, of the phoria test methods. New test methods must be devised if this fault is to be overcome.

Measuring the phoria. The customary method for measuring the phoria is by cancellation. A rotary prism is adjusted until the apparent displacement of an image, due to the phoria, is eliminated. While this is a clever way for measuring the angular deviation of an eye it cannot be said to be entirely divorced from fusional impulses. What could be closer to the intent of fusion than bringing images into alignment? A method in which the subject did not participate would be preferable and such methods are now available in the form of eye position recorders. With these the position of the eyes is, ideally, known at all times. If such recorders were used in phorometry the phoria could be determined at any instant without the participation of the subject.

Producing dissociation. It has been shown that different dissociating devices gave different phoria results for the same subject. It has also been shown that a device which gave a greater phoria value for one subject could give a lesser one for another. We see from this that the choice of the dissociating device is not a simple matter. The whole concept of dissociation needs examination and notions about it must be clarified.

Dissociation, in an idealized sense, means that there are no visual stimuli for a change in vergence. It should also mean that there is no inhibition for a vergence change whose origin is independent of the fusion mechanism. It has already been pointed out, by Westheimer and Mitchell, that similar images may be separated vertically and still act as a stimulus for a vergence change.[43] Herein lies one of the flaws in the prism-diplopia method of dissociation. The same authors have also shown that dissimilar objects can act as a stimulus for vergence changes. This strikes at the basic principle of the Maddox-rod. The present study has confirmed these findings and has also shown that the cover test is not effective in eliminating fusional tonus. The slope of the cover test curve without supplementary dissociation, Figure 23, proves this. If none of these methods are above suspicion, it seems that we must put them aside and look again at the problem of dissociation.

A dissociating device comprises two parts which are the dissociator and the target. For example, the Maddox-rod is a dissociator and the lamp bulb and other details seen by the subject comprise a target. In this example, the target must be a small bright object otherwise the system will not work. The interdependence of the dissociator and the target is not as obvious in the case of the dissociating prism because everything is seen double. If the target had a grid of lines marked on it, similar to graph paper, it is evident that the subject could fuse images even though dissociated. The same thing can happen if a plain sheet of paper is wrinkled or the grain of the paper can be seen. From these examples, it is clear that the target and the dissociator must be thought of as a dissociating unit and the target must be matched to the dissociator for the desired results to be obtained.

New dissociating unit. I should like to propose a new dissociating unit with the target being random dot patterns in polarized light and the dissociator being polarization selective material placed before the subject's eyes. Anyone familiar with the work of Julesz on random dot stereograms will recognise this choice as being based on techniques that are already developed.[17] In the present case, the random dot pattern seen by one eye must be uncorrelated with that seen by the other. All the dots seen should appear to lie in the same plane, which is the plane of the target, and the dots or other forms seen should not act in any way as a stimulus for fusional eye movements.

A patterned surface is required for the target because otherwise an empty field may be formed. If an empty field forms, the test conditions are indeterminate since the part of the field in which there is no change in contrast will be filled in by the visual cortex.[45] Another reason for a surface with visible details is that these are necessary as a stimulus for accommodation.

The dissociating unit proposed here has never been tried. The proof of its supposed merits can only be obtained by a scientific study. If it does give the results hoped for, it could be used as a standard against which other phoria methods could be evaluated. This unit should be used in conjunction with an eye position monitor. If this were not possible a system of polarized reference marks could be used for determining the amount of the phoria. Such a subjective method would suffer from the disadvantages already mentioned.

CHAPTER VII

SUMMARY

The original aim of this project was to produce a computer-controlled phorometer which would serve to measure lateral heterophoria values in a time sequence. This goal has been achieved and the results obtained using this phorometer are of a quality never before obtained. The measurement of the phoria in a time sequence has revealed details concerning the nature of the phoria which would not be observed by any other means.

Although it was originally intended to restrict the phorometer's use to the von Graefe test method, it was soon necessary to include other test methods and other means of dissociation. Among the test methods used were the Maddox-rod drop, the dissociating prism drop, the lens drop, the automatic cover test, the continuously adjustable prism, the fixation disparity phoria and the fused-images test. The fused-images phoria test is a completely new one developed during this study.

A reasonably large number of subjects were tested by the various methods and many of the subjects were re-tested. The results of these tests enable a comparison to be made between the various methods. The constancy of the performance of the tests, due to computer-control, shows differences in the results which cannot be attributed to errors. These differences are so striking that their presence raises doubts about the utility of the various methods of dissociation and the value of phoria tests that are performed manually.

The scope of the study expanded with every unexpected finding until the project became a pilot study on automated phorometry. Anyone intending to investigate heterophoria will probably want to use methods that have been pioneered in this study.

Although no phoria test was found faultless, it would seem that the Maddox-rod method is among the most subject to fusional interference. The least subject to such interference is the automatic cover test with prism-diplopia supplementary dissociation.

It is interesting to note that the method giving the greatest phoria is not always the same from subject to subject. This suggests that the phoria is the result of the workings of a more complex mechanism than might have been expected.

The fused-images test method was particularly useful when applied to a subject with a visual weakness such as asthenopia or strabismus. A subject with a history of strabismus, corrected by surgery, was tested and found to converge when stimulated to diverge and vice versa. No other test available could have extracted this information. This demonstrates a use for this test in ophthalmology and orthoptics.

A recent theory on heterophoria, Crone's, was not substantiated by the results of this study. The associated horizontal phoria was measured automatically and when compared with the other phoria results was not found to be directly related to them. If there is a link between the disparity and the phoria, it must be an indirect one.

A new concept of phoria measurement has been proposed and a new definition of heterophoria given. Further study is needed to see whether or not these are of value. While the computer-controlled phorometer is desireable for studies such as were described here, it is suggested that objective measurements of eye position are to be preferred in the future.

CHAPTER VIII

CLAIMS TO ORIGINALITY

The conception of the experiments, the design of the equipment and its construction, the interfacing, the programming and the subsequent analysis of the data were all done by myself. The idea that the phoria should be measured continuously originated with my thesis director, John Outerbridge. The actual implementation of continuous measurements came about as a by-product of the work done on the automatic cover test.

The following list includes the major innovations which were associated with this work. These are:

1. The stepping prism is my original concept and to date all design and construction, both mechanical and electrical, have been done by me.

2. The interface circuitry used to control the stepping prism was designed and constructed by me.

3. The concept of the computer-controlled phorometer is original as is the specification of the test procedures and their programming.

4. The dropping of the dissociating device or lens is a new procedure which enables the time course of the phoria to be followed or modified.

5. The fused-images test is original.

6. The concept of delta-vergence is original.

7. The discovery of a clinical use for the fused-images test, in connection with strabismus, may be of value.

8. Heterophoria has been re-defined and a new means has been proposed for determining it.

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APPENDIX

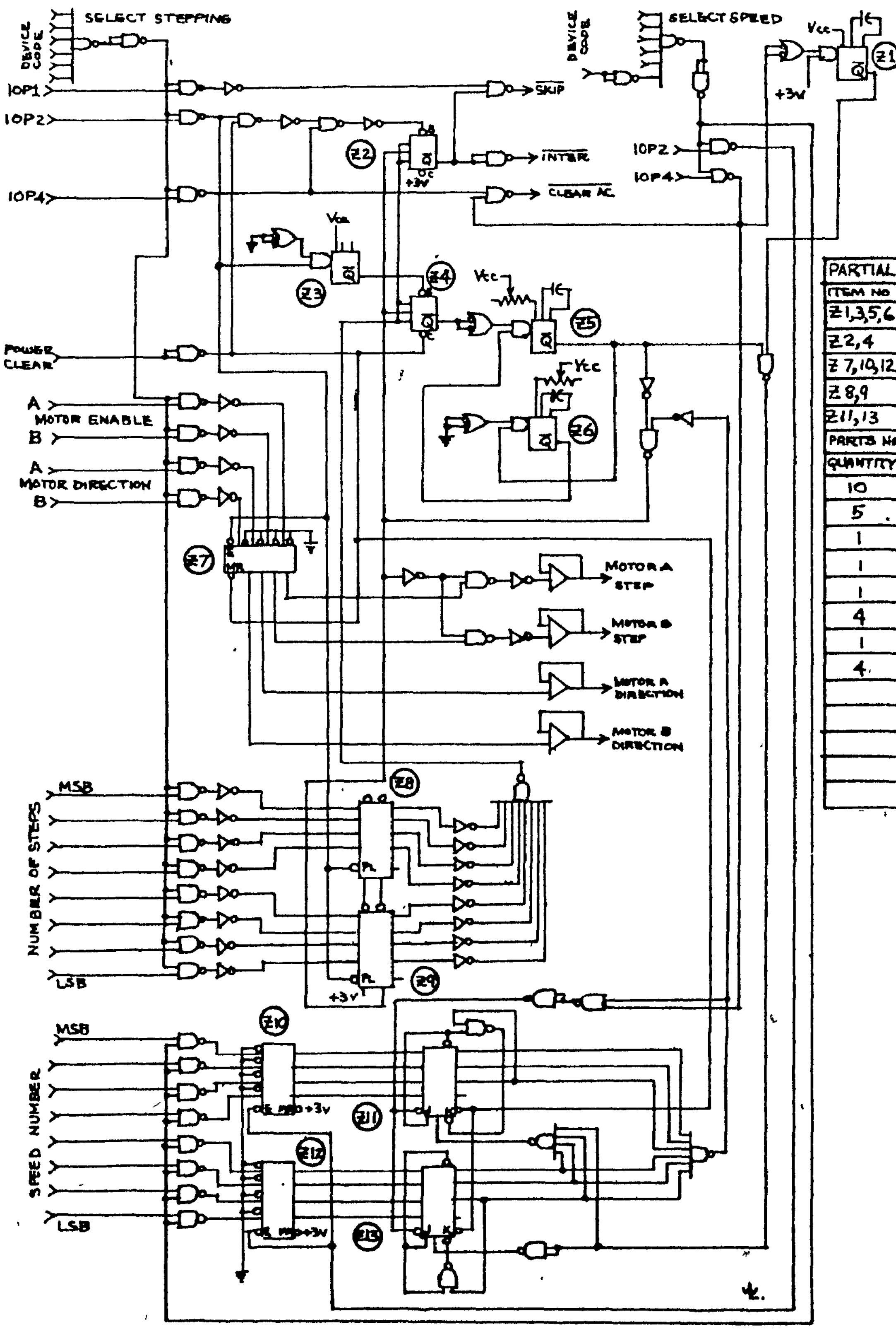
APPENDIX A.

THE CONVERSION FROM PRISM DIOPTERS(Δ) TO ANGLE OF DEVIATION

PRISM POWER (Δ)	DEVIATION (deg.)	PRISM POWER (Δ)	DEVIATION (deg.)
0	0.0	16	9.09
1	0.58	17	9.64
2	1.15	18	10.20
3	1.71	19	10.75
4	2.29	20	11.31
5	2.86	21	11.86
6	3.43	22	12.40
7	4.00	23	12.95
8	4.57	24	13.49
9	5.14	25	14.03
10	5.71	26	14.57
11	6.27	27	15.11
12	6.84	28	15.64
13	7.40	29	16.17
14	7.97	30	16.70
15	8.53		

APPENDIX B.

STEPPING PRISM CONTROLLER/INTERFACE CIRCUIT DIAGRAM



PARTIAL PARTS LIST	
ITEM No	FAIRCHILD No
Z1,3,5,6	74121
Z2,4	9L24
Z7,10,12	9314
Z8,9	9366
Z11,13	9300
PARTS NOT ITEMIZED	
QUANTITY	FAIRCHILD No
10	9L00
5	9L04
1	93L14
1	9002
1	9004
4	9007
1	9012
4	741

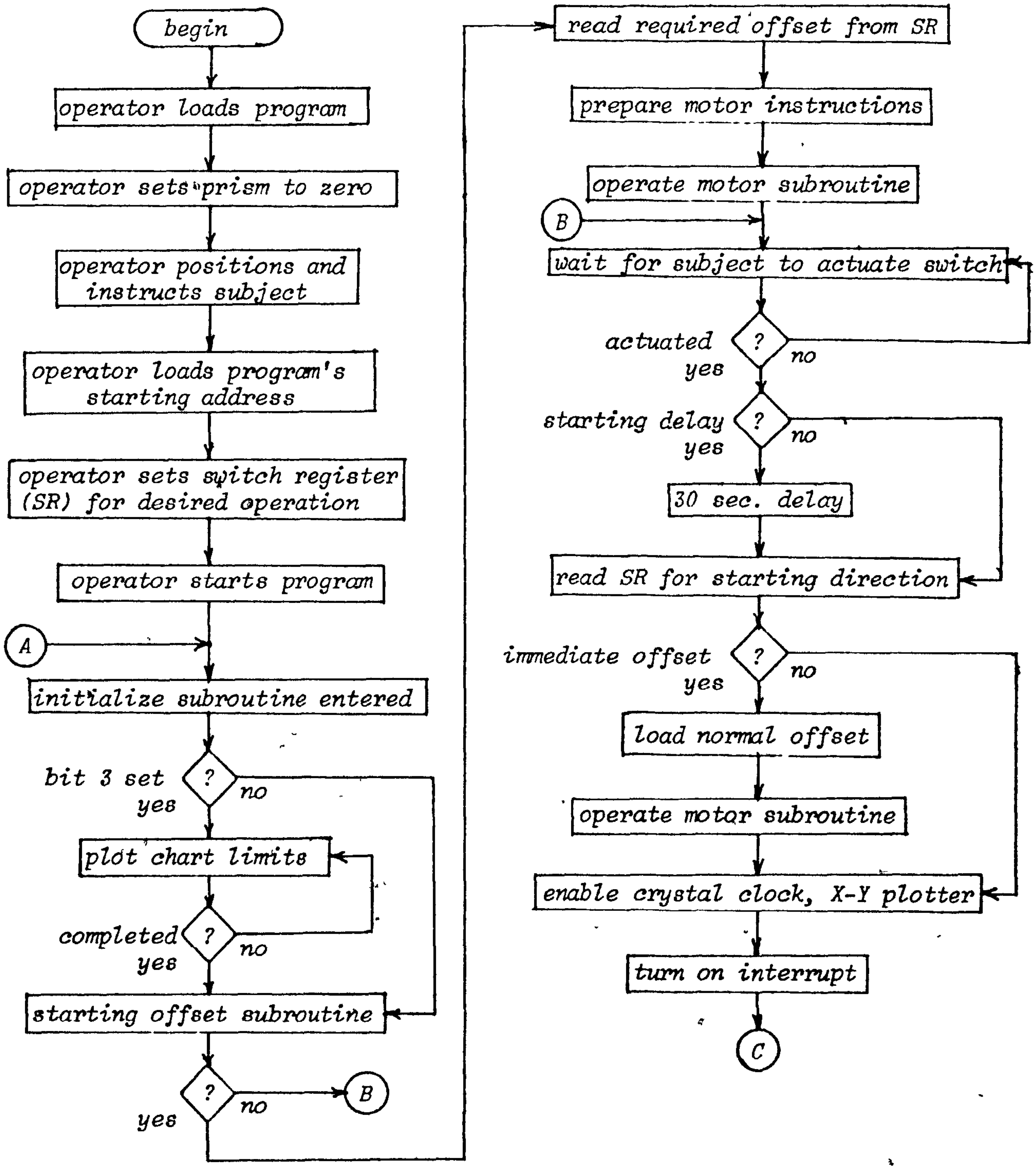


Figure C1. An outline of the programmed procedure for the prism-diplopia test.

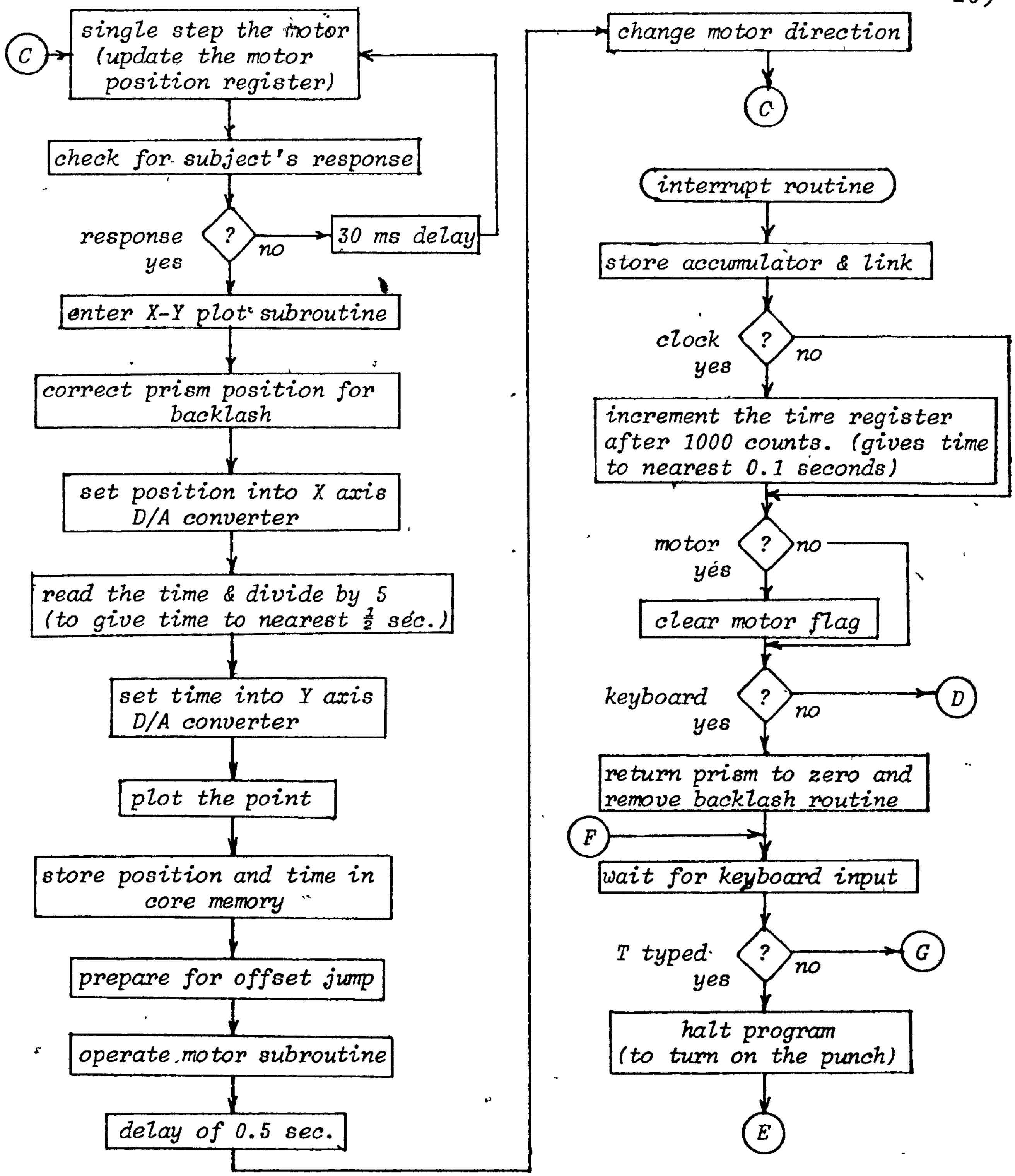


Figure C1. (continued)

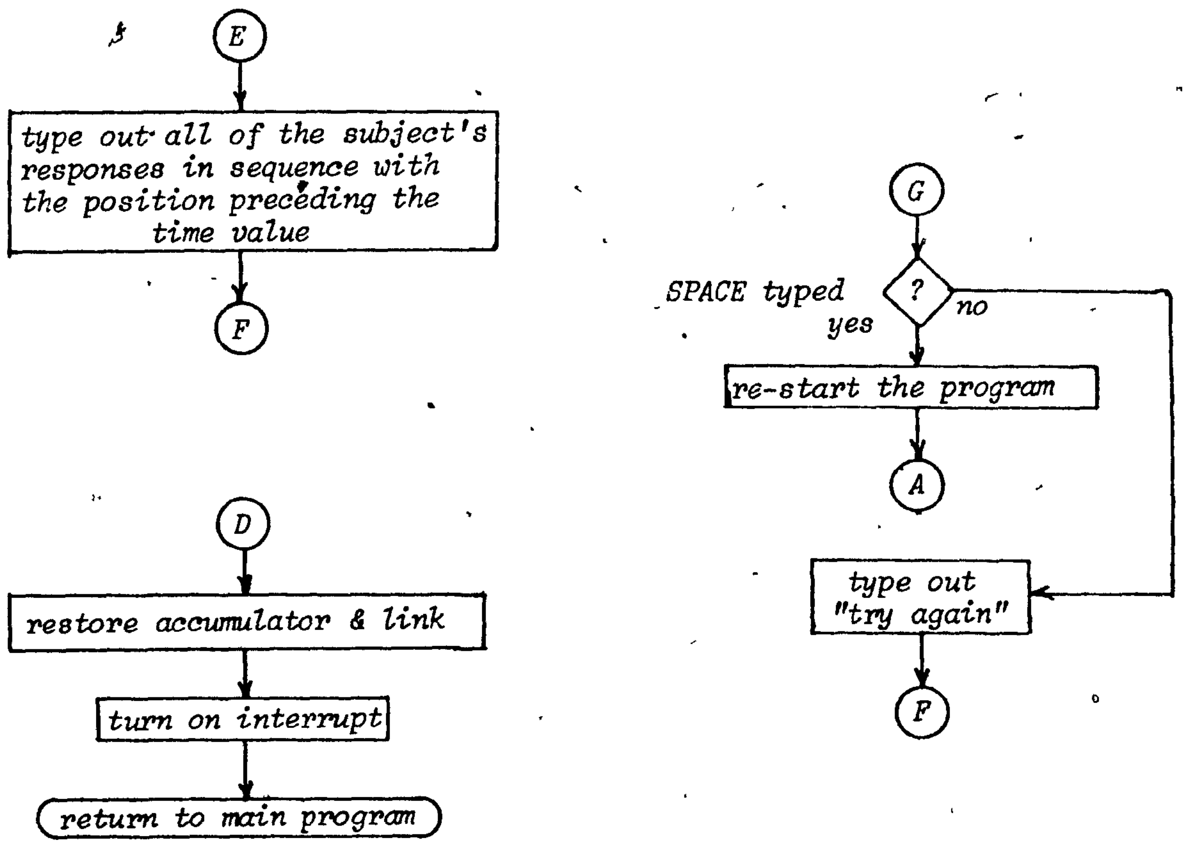


Figure C1. (continued)

APPENDIX C.

TABLE C1.

PHOROMETER, SWITCH REGISTER BIT ASSIGNMENT

USAGE	BIT NUMBER											
	0	1	2	3	4	5	6	7	8	9	10	11
Starting address	1	1	0	0	0	0	0	0	0	0	0	0
Prism base left			0									
Prism base right			1									
Starting delay				1								
Plot chart limits					1							
Starting offset (from 1 to 128 steps)						X	X	X	X	X	X	X

APPENDIX D.

FORTRAN PROGRAM FOR THE RE-FORMATTING OF PHORIA DATA

```
      PRØGRAM THINA (INPUT,ØUTPUT,TAPE 60=INPUT)
      CØMMØN/BLKA/B(1000),D(30),M
      DATA (D(K),K=2,13)/12*11./,(D(K),K=14,17)/4*12./,D(1)/10./
      DATA (D(K),K=18,20)/3*13./,(D(K),K=21,23)/3*14./,D(24)/15./
      DATA D(25)/16./,D(26)/17./,D(27)/19./,D(28)/22./
      DATA D(29)/23./,D(30)/29./
      CALL DATIN(B,M)
      CALL DATØUT(B,M)
      STØP
      END
      SUBRØUTINE DATIN(A,N)
      CØMMØN/BLKA/B(1000),D(30),M
      DIMENSIØN A(1000),N(1)
      DØ 99 I=1,1000
      A(I)=0.0
   99 CØNTINUE
      I=0
    1 READ 20,A(I+1)
   20 FØRMAT(F5.0)
      IF (A(I+1)-90000.) 3,2,4
    3 I=I+1
      GØ TØ 1
    4 PRINT 19
   19 FØRMAT(1X,31HNUMBER BIGGER THAN 90000, ERRØR)
      GØ TØ 100
    2 J=I
      DØ 200 I=1,J,2
      C=A(I)
      IF(C) 6,12,8
    6 C=ABS(C)
    8 K=1
      DA=0.0
      G=0.0
   13 DA=DA+D(K)
      IF(DA-C) 9,10,11
   11 C=G+(1-(DA-C)/D(K))
      GØ TØ 12
   10 C=G+1.0
      GØ TØ 12
    9 K=K+1
      G=G+1.0
      GØ TØ 13
   12 C=SIGN(C,A(I))
      A(I)=C
  200 CØNTINUE
```

APPENDIX D.

FORTRAN PROGRAM (CONT.)

```
    N=J
100 RETURN
    END
    SUBRØUTINE DATØUT(A,N)
    CØMMØN/BLKA/B(1000),D(30),M
    DIMENSIØN A(1000),N(1),C(8)
    K=N/2
    PRINT 29,K
 29 FØRMAT(8X,I3,* RESPØNSES.  CØLUMN D IN PRISM DIØPTERS.*)
    PRINT 26
 26 FØRMAT(8X,*THE SIGN + = PRISM BASE RIGHT.*)
    PRINT 27
 27 FØRMAT(8X,*CØLUMNS T SHØW THE TIME ØF THE RESPØNSE IN SECØNDS.*)

    PRINT 25
 25 FØRMAT(8X,4(3X*D*6X*T*5X))
    DØ 30 I=1,88,2
    L=2
    C(1)=A(I)
    C(2)=A(I+1)/100
    IF(N-87) 60,61,62
 62 L=L+2
    C(3)=A(I+88)
    C(4)=A(I+89)/100
    IF(N-175) 60,61,64
 64 L=L+2
    C(5)=A(I+176)
    C(6)=A(I+177)/100
    IF(N-263) 60,62,66
 66 L=L+2
    C(7)=A(I+264)
    C(8)=A(I+265)/100
 60 PRINT 31,(C(J),J=1,L)
 31 FØRMAT(8X,4(F5.1,F7.1,4X))
 30 CØNTINUE
 61 PRINT 32
 32 FØRMAT(//////////)
    RETURN
    END
```

APPENDIX D.

TABLE D1

THE NUMBER OF MOTOR STEPS WHICH CORRESPOND TO THE POWER OF THE ROTARY PRISM. THE POWER IS EXPRESSED IN PRISM DIOPTERS.

POWER (Δ)	STEPS INTERVAL	STEPS CUMULATIVE	POWER (Δ)	STEPS INTERVAL	STEPS CUMULATIVE
0		0	16		178
	10			12	
1		10	17		190
	11			13	
2		21	18		203
	11			13	
3		32	19		216
	11			13	
4		43	20		229
	11			14	
5		54	21		243
	11			14	
6		65	22		257
	11			14	
7		76	23		271
	11			15	
8		87	24		286
	11			16	
9		98	25		302
	11			17	
10		109	26		319
	11			19	
11		120	27		338
	11			22	
12		131	28		360
	11			23	
13		142	29		383
	12			29	
14		154	30		412
	12				
15		166			
	12				

APPENDIX E

TABLE E1

DATA TYPEOUT FOR SUBJECT J.C., FIGURE 7.
THE ORIGINAL TYPEOUT WAS IN A SINGLE COLUMN.

+0002	-0064	-0069	-0083
0003	0444	0909	1362
-0023	-0068	-0066	-0089
0019	0470	0935	1389
-0036	-0065	-0078	-0080
0049	0496	0965	1418
-0031	-0072	-0076	-0078
0076	0524	0990	1442
-0046	-0065	-0075	-0074
0107	0552	1015	1468
-0045	-0067	-0077	-0072
0132	0577	1039	1493
-0060	-0067	-0082	-0069
0163	0602	1066	1519
-0050	-0087	-0079	-0086
0191	0635	1092	1550
-0045	-0068	-0085	-0074
0215	0667	1120	1579
-0048	-0073	-0077	-0081
0239	0694	1148	1607
-0045	-0061	-0081	-0070
0263	0732	1174	1636
-0053	-0073	-0078	-0087
0285	0753	1200	1667
-0065	-0064	-0085	-0072
0314	0781	1228	1698
-0067	-0068	-0088	-0081
0339	0808	1252	1726
-0069	-0066	-0093	-0079
0364	0834	1278	1752
-0064	-0073	-0091	
0391	0861	1304	
-0067	-0074	-0098	
0417	0886	1332	

NOTE: The minus (-) sign indicates prism base left. See the text for details on the format.

APPENDIX E

TABLE E2. THE SAME DATA AS IN TABLE E1, SUBJECT J.C., AS ARRANGED BY A LARGER COMPUTER.

67 RESPONSES. COLUMN D IN PRISM DIØPTERS.
THE SIGN + = PRISM BASE RIGHT.
CØLUMNS T SHØW THE TIME ØF THE RESPØNSE IN SECØNDS.

D	T	D	T	D	T	D	T
-4.7	2.4	-9.0	116.1				
-6.1	4.6	-7.5	119.6				
-5.8	7.3	-6.8	122.1				
-6.7	9.7	-7.1	124.7				
-7.3	12.8	-7.2	127.5				
-7.5	15.5	-7.3	130.2				
-6.7	17.9	-6.5	132.7				
-7.9	20.2	-6.6	135.4				
-7.0	22.6	-6.5	138.0				
-7.8	25.1	-7.4	140.4				
-7.0	27.5	-6.5	142.8				
-7.1	30.2	-5.5	146.0				
-7.2	33.1	-5.4	148.7				
-7.6	35.7	-6.0	151.2				
-7.6	38.4	-5.3	153.6				
-7.6	41.2	-5.6	156.2				
-6.6	43.6	-5.8	159.0				
-7.5	46.0	-6.1	161.7				
-6.6	48.4	-5.7	164.3				
-6.4	51.3	-5.0	167.3				
-5.6	53.8	-4.6	169.9				
-6.5	56.2	-4.5	172.7				
-6.0	58.7	-4.9	175.6				
-6.5	61.3	*00.0	0.0				
-6.7	64.2	0.0	0.0				
-7.0	66.9	0.0	0.0				
-6.8	69.6	0.0	0.0				
-7.5	72.0	0.0	0.0				
-6.6	74.5	0.0	0.0				
-7.6	76.8	0.0	0.0				
-7.5	79.6	0.0	0.0				
-7.9	82.2	0.0	0.0				
-7.9	84.9	0.0	0.0				
-8.1	87.6	0.0	0.0				
-7.4	90.1	0.0	0.0				
-8.4	92.4	0.0	0.0				
-8.1	95.0	0.0	0.0				
-8.3	97.7	0.0	0.0				
-8.5	100.6	0.0	0.0				
-9.5	102.8	0.0	0.0				
-8.8	105.3	0.0	0.0				
-9.1	107.9	0.0	0.0				
-9.0	110.7	0.0	0.0				
-9.0	113.4	0.0	0.0				

APPENDIX F

REMARKS ON THE INTERPRETATION OF FUSED-IMAGES RESULTS

The fused-images test is entirely new and although it is a relatively simple test procedure it is not easy to interpret the results without a more detailed explanation than is given in the text. The offset jump, which is the dissociating means, acts as a step function input to the vergence component of the visual system. After the offset jump is executed, the prism is slewed back toward its position before the jump. Therefore the input function must be classified as a kind of saw-toothed ramp in which the direction of the tooth is inverted at each repetition. The form is shown in Figure F1. Different response patterns on the part of the subject will result in differences in the input as is shown in the upper part of the figure. The midpoints and delta-vergence plots calculated from this data are shown directly under the input wave form. The point at which the subject responded is indicated by the small circle and it is easy to see how the response pattern of the subject can alter the input wave form. The calculations required to determine the midpoints and delta-vergence for the first 10 responses in example C of the figure, are shown in Table F1.

Example A of Figure F1 is intended to illustrate what happens when the subject is uninfluenced by the stimulus to change vergence. Although the subject is able to fuse images under normal circumstances, he does not do so under the test conditions. Thus the images are not fused until the prism returns to the power it had at the time of the last response. An example of this type of response is given in Figure 10.

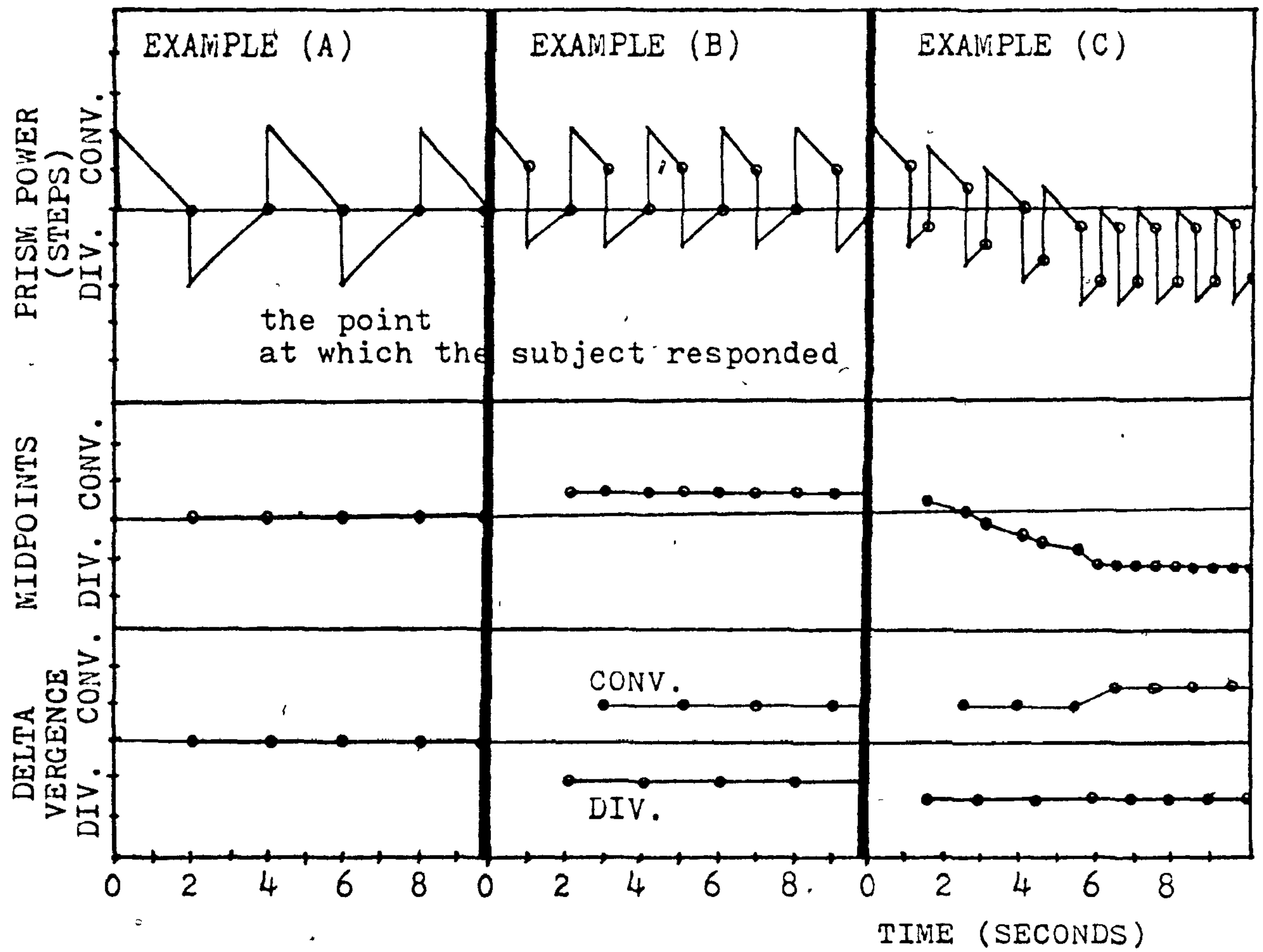


Figure F1. The waveform of the visual input will be altered by the subject's response pattern when the fused-images test is used. Refer to the text for details.

APPENDIX F

TABLE F1

SAMPLE MIDPOINTS AND DELTA-VERGENCE CALCULATIONS

RESPONSE	TIME (SEC)	PRISM POSITION (STEPS)	DELTA VERGENCE (STEPS)	MIDPOINTS (STEPS)
n	t	P	$(P_{n+1} - P_n)$	$(P_n + P_{n+1})/2$
1	5	+10	-	-
2	7.5	-5	-15	2.5
3	12.5	+5	+10	0
4	15	-10	-15	-2.5
5	20	0	+10	-5
6	22.5	-15	-15	-7.5
7	27.5	-5	+10	-10
8	30	-20	-15	-12.5
9	32.5	-5	+15	-12.5
10	35	-20	-15	-12.5

If the offset jump stimulates a vergence change, the idealized response pattern might look like those in Figure F1, parts B and C. In part B it is assumed that the amount of the vergence change was identical in both directions. Part C illustrates what happens when the subject does not alter his vergence as much when stimulated in one direction as he does when the stimulus is in the other direction. In this example the vergence change in the divergent direction is greater than that in the convergent direction for the first 6 seconds. Thereafter the responses are shown as the same in either direction.

The midpoints and delta-vergence plots in example A show that no "false phoria" occurs and that all points fall on the zero line of the delta-vergence graph. Example B illustrates what is meant by the "false phoria". Even though the subject changed his vergence equally in both directions, the midpoints curve is seen to be shifted away from the zero line. In this case the curve suggests esophoria. If the first offset jump had been made in the divergent direction the curve would have suggested exophoria. In this way it is possible for the midpoints plot to give a false phoria since the phoria is not a contributing factor to the position of the curve in this graph. The same reasoning can be applied to the symmetrical responses, after 6 seconds, in example C.

The delta-vergence graph of example B shows how vergence changes give rise to two curves, one for the convergence stimulus and the other for the divergence stimulus. The distance from the zero line indicates the amount of the vergence change and its direction. The delta-vergence curves in example C show that asymmetrical vergence responses are easily seen from an examination of the curves.

It is impossible for the delta vergence value to exceed the value of the offset jump. That is to say, an offset jump of 5Δ in the convergent direction cannot result in a convergence stimulus curve with any value greater than 5Δ. A subject who responded quickly to the vergence stimulus might have a delta-vergence curve close to 5Δ but no value of 5Δ could be recorded unless, by accident, he pushed the actuating switch twice in quick succession. On the other hand it is possible for responses to a convergence stimulus to fall on the divergence side of the graph and vice versa. If the amount of this negative response is large enough, it is possible for the response to a convergence stimulus to exceed the amount of the offset jump limit in the divergence direction. An example of this sort of response pattern is shown in Figure 29.

APPENDIX G

THE ORIGINAL DATA TYPEOUT FOR THE RESULTS OF SUBJECT J.L.

+0039
0032
+0006
0067
+0011
0092
+0015
0114
+0109
0170
+0027
0222
+0103
0271
-0099
0365
+0097
0456
-0075
0539
+0031
0599
-0083
0661
+0088
0744
-0026
0807
+0076
0865
+0005
0913
+0061
0956
-0013
1005
+0052
1051
+0018
1086
+0081
1131
+0028
1173
+0051
1204
+0016
1239
+0066
1280
+0046
1310
+0056
1337
-0004
1381
+0020
1413
+0014
1438
+0036
1469
+0033
1493
+0061
1526
+0055
1552
+0058
1576
+0041
1605
+0030
1625
+0047
1643
+0085
1679
+0036
1720
+0056
1750

APPENDIX G

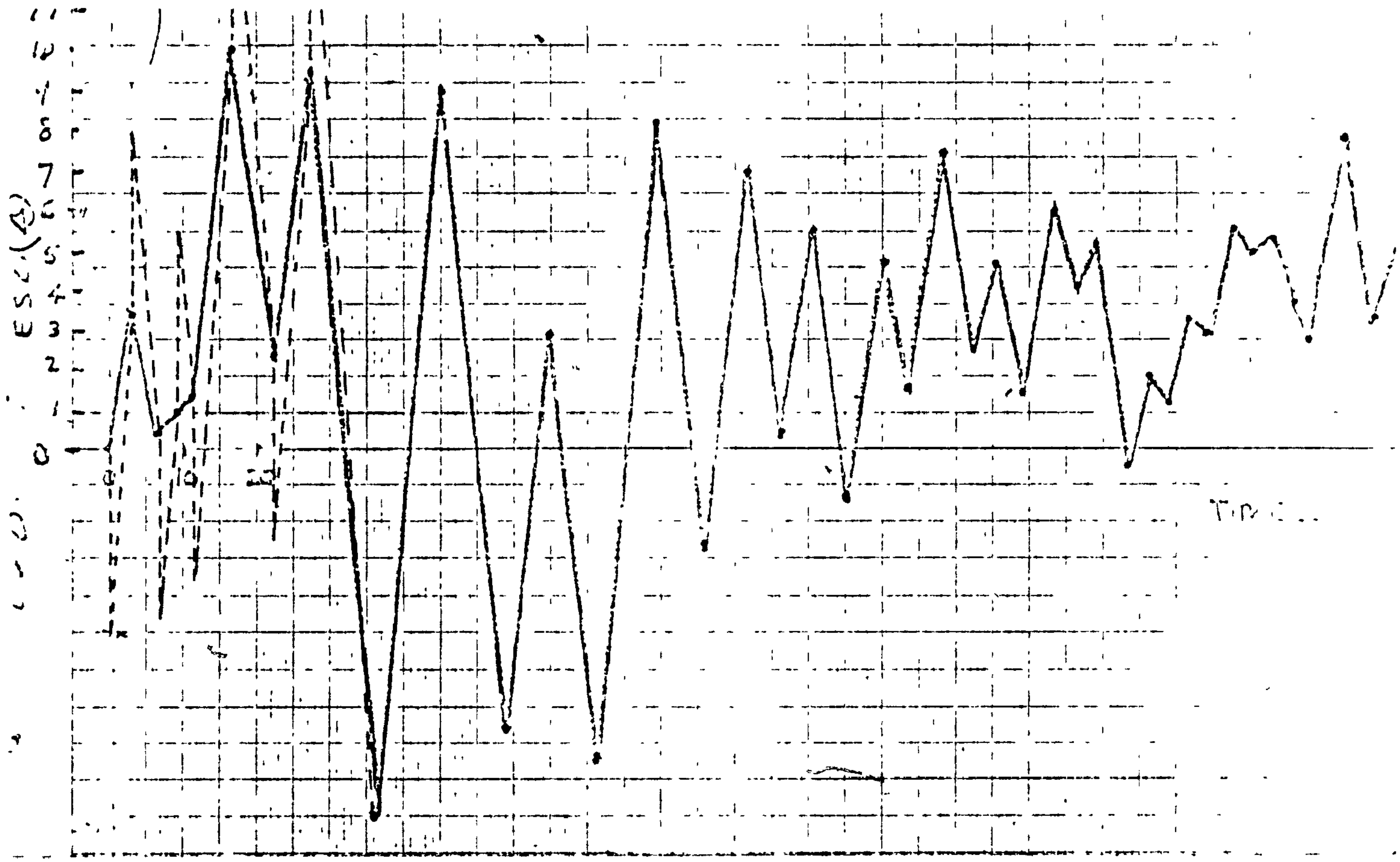


Figure G1. A copy of the original data point plot for subject J.L. whose midpoints and delta-vergence plots, from this data, are shown in Figures 28 and 29. The solid lines joining the points were added by hand after the points were plotted by the X-Y plotter. The dashed lines show how the prism's power changed during the test and are included to prove that the delta-vergence interpretation of the data is correct.