BINOCULAR SINGLE VISION

PSYCHOPHYSICAL STUDIES ON UNDERLYING SENSORY AND MOTOR PROCESSES

The picture on the cover shows a collection of 'twos' of variable size and orientation which may be interpreted as a 'one'. The picture symbolizes the conclusion in this thesis that singleness of binocular vision, in spite of disparities between the retinal images in the two eyes, seems to be an interpretation (the 'one') of poorly reproducible, inaccurate and inconspicuous but nevertheless perceivable cues pointing to doubleness of vision (the 'twos').
The picture was made in analogy to Figure 60 in the book 'Gödel, Escher and Bach: an Eternal Golden Braid' by Douglas R. Hofstadter.

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PSYCHOPHYSICAL STUDIES ON UNDERLYING SENSORY AND MOTOR PROCESSES

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE
GENEESKUNDE
AAN DE ERASMUS UNIVERSITEIT ROTTERDAM
OP GEZAG VAN DE RECTOR MAGNIFICUS
PROF. DR. J. SPERNA WEILAND
EN VOLGENS BESLUIT VAN HET COLLEGE VAN DEKANEN.
DE OPENBARE VERDEDIGING ZAL PLAATSVINDEN OP
WOENSDAG 4 NOVEMBER 1981 DES NAMIDDAGS
TE 2.00 UUR

DOOR

ARNE LEX DUWAER

GEBOREN TE MAKASSAR

DELFT UNIVERSITY PRESS/1981

PROMOTOR : PROF. DR. G. VAN DEN BRINK
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PROF. DR. H. COLLEWIJN

Aan mijn ouders en Ada

Dit onderzoek was mogelijk dankzij een subsidie van de Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek (Z.W.O.) via de Nederlandse Stichting voor Psychonomie en werd uitgevoerd op de afdeling Biologische en Medische Natuurkunde van de Erasmus Universiteit te Rotterdam.

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I

SYNOPSIS

1.1 INTRODUCTORY REMARKS

The present thesis deals with *binocular single vision.*

By closing one of the two eyes alternately (in particular in the presence of nearby objects), one can easily see that we are confronted with *two* different images of the outside world. Nevertheless, when we look at this world with both eyes we still perceive it for the greater part *singly.* This in spite of the fact that the two images often differ so much that the world would be perceived as clearly double if the same images did not enter the visual system through different eyes but, projected on top of each other, through the same eye. This singleness of binocular vision is accomplished by *motor* processes which use the eye muscles to direct the eyes towards the same point in space, and by *sensory* processes in the brain which avoid *doubling* of the binocular image.

Interpretation of certain types of differences between the images in the two eyes results in *stereopsis* (depth perception) which disappears when one of the eyes is closed. As a result, the observer can assess the occurrence of *these* image differences not only by using the comparatively inconspicuous and inaccurate information provided by image doubling, which is the subject of the present thesis, but also indirectly by using the conspicuous and accurate depth cue. It was decided to avoid this complication by confining the study to those situations where these interfering depth effects did not occur.

The processes underlying binocular single vision have been studied in *psychophysical* experiments. Subjects were asked to make judgments on the percepts evoked by visual stimuli. The procedures and stimuli chosen were such that they practically guaranteed that the judgments were always based on the same information. In this way the mysteriously variable nature of a person's psyche, which is unavoidably involved in the judgments, was restricted.

The material of this thesis consists of eight articles which have been submitted for publication to several international journals. In the present thesis, the articles have been organized according to their subjects to form four chapters (II - V).

1.2 BASIC PROBLEMS ASSOCIATED WITH BINOCULAR SINGLE VISION

The basic problems associated with binocular single vision that are dealt with in the present study will be explained with reference to the diagrams of Fig. 1.

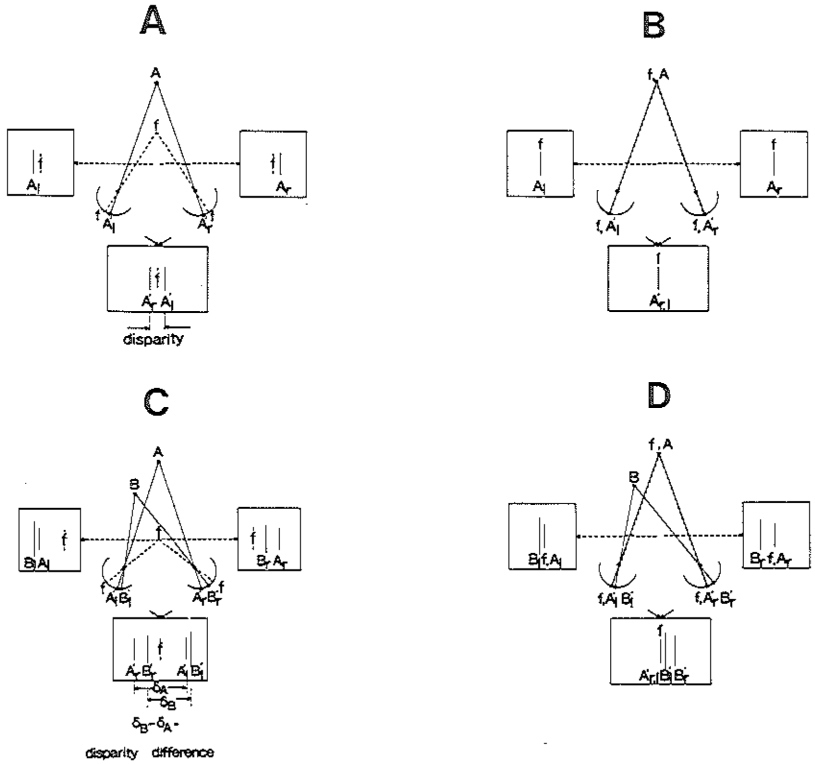


Fig. 1. Diagrams illustrating the basic problems associated with the singleness of vision during perception with both eyes. See text for more detailed information.

Fig. 1A shows a situation where both the observer's eyes are directed towards some arbitrarily chosen location (f) in the binocular space, while the observed object is a vertical line (A) which occupies different relative locations for the two eyes. In this particular example A is located to the left of the left eye's line of sight and to the right of the right eye's line of sight. The difference between the relative locations for the left and right eye results in the stimulation of non-corresponding points on the retinae by the monocular images of A.

The difference between the relative locations for the left and right eye is usually called the disparity. The disparity is zero (by definition) for location (f), because (f) is one of the locations in the binocular space for which the perceived relative locations are the same for the two eyes.

Now the occurrence of a disparity causes the image of the object in question to be represented at *two laterally separated locations* after conjunction of the monocular signals coming from each of the eyes. It would, therefore, be not at all surprising if the object were seen simultaneously at these two locations, i.e. *double*.

This doubling of vision ('*diplopia*') does not usually occur, however. Disparities, especially those around the point at which the observer's gaze is directed, are usually largely eliminated by reflex vergence eye-movements which change the lines of sight of the two eyes in such a way that the images of the object observed fall on corresponding retinal points in the two eyes. Since corresponding retinal points have (by definition) the same location in the perceived binocular space (see Fig. 1B), the object will be seen *single*.

The occurrence of vergence eye-movements is, however, not sufficient for the maintenance of binocular single vision because there are usually residual disparities.

One important cause of residual disparities is that vergence eye-movements are not perfect. They need time to eliminate disparities, they operate with limited accuracy and they make systematic errors. All these causes result in residual disparities called '*fixation disparities*'. A situation like that shown in Fig. 1A, but with reduced and varying disparity, will therefore be more typical for binocular vision than the situation of perfect motor elimination of disparity as depicted in Fig. 1B.

Another major cause of residual disparities is that vergence eye-movements can only eliminate overall shifts (like the disparity of Fig. 1A) and overall rotations. All other types of disparities within a binocularly perceived scene will therefore lead to uncorrectable residual disparities, even if vergence eye-movements were operating perfectly.

An example of a scene containing uncorrectable residual horizontal disparities is shown in Fig. 1C. We see here two objects A and B, arranged in such a way that the disparity δ_A for the image of A differs from that (δ_B) for the image of B. This disparity difference is possible because of the lateral separation of the two eyes. When vergence-movements now eliminate the disparity δ_A for the image of A, there will be a residual disparity ($\delta_B - \delta_A$) for the image of B (see Fig. 1D). This disparity can only be eliminated by vergence eye-movements at the cost of a residual disparity ($\delta_A - \delta_B$) for the image of A. It should be noticed that the disparities ($\delta_B - \delta_A$) or ($\delta_A - \delta_B$) are not the only uncorrectable residual disparities in Fig. 1C. Object B is closer to the left eye than it is to the right eye, so the image of B will be larger in the left eye than in the right one. This apparent size difference results in disparities that cannot be fully eliminated by vergence eye-movements either.

Apart from these uncorrectable residual disparities due to the lateral separation of the eyes, there will usually also be uncorrectable residual disparities due to differences in properties between the two eyes. A rather common difference of this type is that between the refractive powers of the two eyes, which results in an apparent size difference called 'aniseikonia'.

Residual disparities that are not eliminated by vergence eye-movements do not always lead to diplopia. Panum (1858) found that this could be ascribed to the occurrence of a *sensory disparity threshold* for the perception of diplopia. This '*diplopia threshold*' forms the basis for one of the two major aspects of sensory evaluation of disparities. The other aspect is '*stereopsis*' (depth perception), which was first described by Wheatstone (1838). Wheatstone discovered that a disparity difference in the *horizontal* direction (e.g. $\delta_A - \delta_B$ in Fig. 1C) is a necessary and sufficient stimulus for the perception of stereoscopic depth difference. This impression of stereoscopic depth when two monocular 2-dimensional stimuli with horizontal disparity differences are observed is the basis for the popular 'stereo viewer'. It is interesting to note from a comparison of the Figs. 1C and 1D that the disparity difference does not change when the fixation point (f) changes. This explains why stereopsis is not being affected by varying small fixation disparities, due to involuntary eye-movements (see chapter III).

Singleness of binocular vision despite disparities as well as doubleness of binocular vision due to disparities may be perceived with and without stereoscopic depth differences (see e.g. Ogle, 1964). This illustrates that the depth cue about the occurrence and magnitude of disparities - which is accurate and conspicuous - is added to the information about image doubling due to the disparity - which is less accurate and conspicuous. The processes underlying the diplopia threshold are therefore usually studied for disparities in the *vertical* direction, thus avoiding the complications caused by the occurrence of stereoscopic depth differences (see e.g. Kertesz, 1972; Kaufman and Arditi, 1976). The same strategy will be followed in the present study.

Summing up, we may state that the factors underlying binocular single vision are the tendency for visual disparities to be corrected by vergence eye-movements, in combination with the occurrence of a sensory threshold for the perception of diplopia, that should be differentiated from stereopsis.

1.3 FORMULATION OF THE PROBLEMS

Consultation of the literature at the start of the present study revealed one major issue which had not really been tackled and another which though investigated was still unresolved. The former concerns the *cooperation* between vergence eye-movements aimed at minimizing the disparities on the retinae of the two eyes on the one hand and the sensory processes underlying the diplopia threshold on the other. The latter concerns the *nature* of the sensory processes underlying the diplopia threshold. A major traditional view is that the occurrence of this threshold is due to a fusion mechanism eliminating retinal disparities (see e.g. Kertesz, 1972; Kertesz and Sullivan, 1976). According to the opposing view there is no 'real threshold' for disparities and, consequently, no sensory fusion mechanism. The diplopia threshold would be just a disparity value set by applying a *lenient* criterion to judge the deterioration of singleness due to the disparity (Kaufman and Arditi, 1976). It was the objective of the present study to throw light on both these issues. This was done by performing psychophysical experiments using primarily horizontal lines with vertical disparity between the images in the two eyes as test stimuli.

1.4 TOWARDS AN UNDERSTANDING OF THE SENSORY PROCESSES UNDERLYING BINOCULAR SINGLE VISION

The nature of the sensory processes underlying the diplopia threshold has been studied first by a detailed analysis of the nature of the diplopia threshold (see Chapter 2.1). The overall results of this analysis strongly suggest that the diplopia threshold is indeed not a 'real' threshold, i.e. not the rigid boundary of a dead zone in which the disparities are eliminated. It appears to be rather a disparity value set by a lenient criterion for singleness of vision which leads to useful interpretation of the percept of the stimulus without

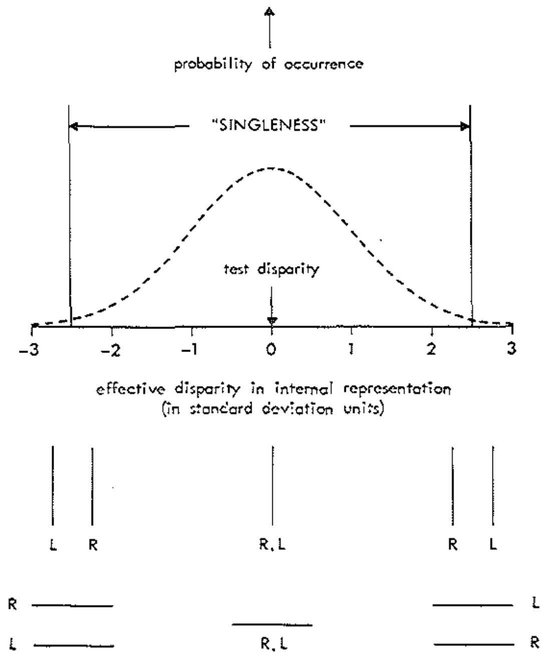


Fig. 2. Schematic representation of the distribution of effective disparity in internal representations of a stimulus without disparity. The distribution function shown is a normalized Gaussian one. The lower part of the figure gives the locations in binocular space of a line L in the left eye and a line R in the right eye when the disparity between L and R is negative, zero or positive. Vertical lines are depicted with horizontal disparity and horizontal lines with vertical disparity.

disparity, given the variability of this percept due to intrinsic noise in the disparity domain. This statement will be clarified with reference to Fig. 2.

The broken line in Fig. 2 represents the distribution of the effective disparity in a large number of internal representations of the stimulus *without* disparity. The effective disparity can differ from zero because of the intrinsic noise in the disparity domain which reflects the limited accuracy and reproducibility with which disparity information is coded. The vertical bars indicate the disparity values where 'singleness' typically ends. It may be noticed that the absolute magnitude of these values is the same for positive and negative effective disparities. This is due to the fact that disparities of opposite sign produce the same separations between the monocular images (see lower part of Fig. 2). The disparity values where 'singleness' ends correspond approximately to the maximum values of the effective disparity in internal representations of the stimulus without disparity. Comparison of the whole area under the distribution function and the part of this area between the vertical bars shows that nearly all internal representations of the stimulus without disparity will be classified as 'single'. This makes this particular singleness criterion useful. It may be regarded as a lenient criterion, since subjects are capable of using sharper criteria corresponding to smaller disparity values. A serious drawback of the use of sharper criteria is their restricted utility, due to the fact that the percepts of the stimulus without disparity can be classified in two different ways when sharper criteria are used.

It will be clear that the diplopia threshold as defined above appears to be brought about in a rather arbitrary way by use of a lenient criterion amidst many possible criteria. However, this threshold remains of interest because of its fairly large size - which reflects the fact that the changes in the binocular percepts introduced by the disparity are processed by the visual apparatus in such a way that the overall visual impression received by the subject is relatively inconspicuous and vague: a separation equal to the disparity can be observed much more clearly when the same monocular stimuli are presented to a single eye.

Our study of the nature of the diplopia threshold provides strong indications that the occurrence of this threshold should *not* be ascribed to a sensory fusion mechanism that gradually eliminates disparities. This conclusion was confirmed by the results of a detailed analysis of the effect of the presentation time of a vertical disparity on its detection and recognition on the basis of deteriorated singleness (see Chapter 2.2). If a fusion mechanism were involved, the detection and recognition of the disparity should get worse at longer presentation times, because the dynamics of this perceptual mechanism should give better elimination the longer the disparity is presented. The detection and recognition was, however, found to *improve* with increasing presentation time. This almost makes it untenable to assert that the occurrence of diplopia thresholds is a result of a sensory mechanism that gradually eliminates disparities. It is much more likely that the occurrence of diplopia thresholds is due to some kind of failure of a 'signal-detection' process (disparity being the signal) aimed at revealing the disparity.

This assertion was strongly supported by the finding that it appeared to be possible to formulate a signal-detection model for detection of vertical disparities which holds under a wide variety of stimulus conditions (see Chapter 2.3). This model has two essential features, viz. (a) loss of information about the sign of disparities reflecting the fact that disparities of opposite sign result in the same percept (*cf*. Fig. 2) and (b) the presence of intrinsic noise, reflecting the limited accuracy and reproducibility with which disparity information was found to be coded. A peculiarity of this noise is that its level (the width of the effective disparity distribution of Fig. 2) varies throughout the disparity domain with a minimum at an intermediate non-zero disparity value. In the present study, this minimum is the only psychophysical evidence that the internal representations of small disparities (leading to singleness of binocular vision) might differ from the internal representations of large disparities (leading to doubleness of binocular vision).

The overall results suggest that singleness of binocular vision despite retinal disparities is due to (functional) failure of a sensory detection process aimed at revealing the retinal disparities. This failure seems to be primarily due to the tendency of observers to use lenient assessment criteria, to the presence of intrinsic noise throughout the disparity domain (reflecting the limited accuracy and reproducibility with which disparity information about image doubling is coded) and to loss of information about the *sign* of disparity (reflecting the fact that positive and negative retinal disparities - e.g. image in right eye displaced in an upward direction and in the left eye in a downward direction from the corresponding positions in the two eyes, and vice versa - result in the same amount of doubling of the binocular image).

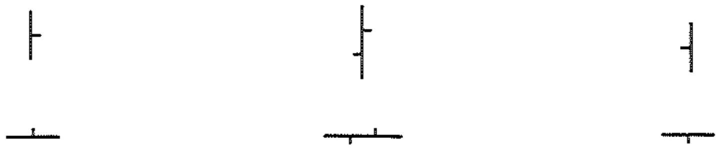
1.5 COOPERATION BETWEEN MOTOR AND SENSORY PROCESSES UNDERLYING BINOCULAR SINGLE VISION

The cooperation between vergence eye-movements aimed at minimizing retinal disparities on the one hand and the processes underlying sensory tolerance to these disparities on the other was studied by comparing the accuracy of vergence eye-movements and the magnitude of the diplopia threshold in the same subjects and under the same stimulus conditions.

The accuracy of vergence eye-movements was assessed in the vertical and horizontal directions by measuring the distribution of the fixation disparities occurring spontaneously during continuous observation of a fixation stimulus (see Chapter 3.1). This accuracy was also assessed in the vertical direction by determining the smallest disparities that, when presented abruptly, initiate vergence eye-movements (see Chapter 3.2).

The accuracy of vergence eye-movements was determined by a subjective alignment method in which the subject judges the relative displacement between dichoptically presented nonius lines (see Fig. 3). The *relative displacement between the nonius lines is a measure of the fixation disparity between the eyes* (Hebbard, 1962; Crone and Everhard-Halm, 1975; see Chapter V). Fixation disparities down to about 0.3' of arc can be detected by this method.

The major finding was that the accuracy of vergence eye-movements is remarkably good in the vertical direction. Vergence eye-movements may be initiated by a vertical disparity in the fovea as small as the angular distance between the centres of two neighbouring receptors. At the periphery of the visual field, they can even be initiated by vertical disparities smaller than the distance between the centres of neighbouring receptors. The vergence eye-movements are so accurate that the residual fixation disparities left are far too



left-eye stimulus

percept in case of fixation disparity

right-eye stimulus

Fig. 3. Principle of the subjective alignment method used to determine the accuracy of vergence eye-movements in the vertical and horizontal direction.

small to result in diplopia.

The vergence eye-movements in the horizontal direction were found to be less accurate than in the vertical direction. The diplopia thresholds for horizontal disparity (being larger than the diplopia thresholds for vertical disparity) are nevertheless substantially larger than the residual horizontal fixation disparities.

The findings conclusively demonstrate that the processing of disparities may be remarkably accurate in both the horizontal and vertical directions, but that the natures of these accurate processes differ essentially in these two directions. *Vertical disparities not containing meaningful information* are accurately *eliminated* by vergence eye-movements. *The meaningful (depth) information* conveyed by relative *horizontal* disparities, on the other hand, is accurately evaluated by *stereopsis*. Conscious perception of image doubling as a result of the *meaningless* part of information about residual vertical and horizontal disparities as such is avoided by *comparatively large diplopia thresholds* and *comparatively inaccurate sensory processing*.

The overall results suggest that the key-factor in the cooperation between vergence eye-movements aimed at minimizing retinal disparities on the one hand and the processes underlying sensory tolerance to these disparities on the other is, that the sensorimotor system controlling vergence eye-movements in response to retinal disparities is more sensitive and accurate than the sensory system controlling the psychophysical assessment of these disparities in terms of image doubling. Retinal disparities, especially those around the fixation point, are thus continuously motorially eliminated by vergence eye-movements with a more than sufficient accuracy.

1.6 BINOCULAR SINGLE VISION UNDER HIGHLY DEMANDING CONDITIONS

Several recently published reports claim a quite surprising reduction of the accuracy of ocular alignment and a rise in the diplopia threshold by more than an order of magnitude when visual tasks are performed under two highly demanding conditions, viz. binocular fixation during active head rotation (Steinman and Collewijn, 1980; Steinman et al., 1981) and forced vertical divergence (Kertesz, 1981).

It should however be noted that in these studies ocular alignment was assessed indirectly by taking the angular position of sucion-type contact lenses mounted to the eyes as a measure of the directions of the visual axis. Moreover, such contact lenses place an unnatural load on the subjects besides the load caused by the highly demanding test conditions themselves; they are thus likely to interfere with the visual apparatus and to distract the subjects from their visual task. It was therefore decided to repeat the above-mentioned experiments with a specially designed afterimage method measuring ocular alignment with the aid of afterimages serving as temporary retinal 'landmarks'; this method is direct, contrary to the suction-type lens method, and certainly interferes much less with the subject's performance of his visual task.

Under these more natural conditions, ocular alignment on an unequivocally defined fixation marker during binocular fixation with active head rotation was found to be an order of magnitude better than previously reported (see Chapter 4.1). The same holds true for ocular alignment on a stimulus during forced vertical divergence, provided that the singleness of binocular vision is not disrupted, e.g. by false correlation of noncorresponding parts of the stimulus (see Chapter 4.2). These new results suggest that it may not be necessary after all to assume the activation of special neuronal processes raising the diplopia thresholds to explain binocular single vision under highly demanding conditions as the above-mentioned authors have done; according to our measurements, the accuracy of ocular alignment is quite high enough to explain this singleness of vision itself.

1.7 CONCLUSIONS

The overall results of the present study suggest that binocular single vision is brought about by (extremely) accurate elimination of disparities by vergence eye-movements in combination with a sensory tolerance. This sensory tolerance reflects our conclusions that (a) singleness of binocular vision is just a lenient criterion amidst the many possible criteria which could be used to judge the disparity information and (b) disparity information about image doubling is inaccurately, inconspicuously and not very reproducibly coded in conscious perception.

The main functions of this sensory tolerance seem to be to avoid diplopia around the fixation point due to comparatively small fixation disparities and to avoid diplopia in the rest of the visual field due to fixation disparities or other types of disparities remaining after the reflexive elimination of disparities around the fixation point by vergence eye-movements.

1.8 CONCLUDING REMARKS

The present study was prompted by unpublished determinations of diplopia thresholds for complex stimuli by Van den Brink (1978), which indicated that diplopia thresholds for vertical disparities in complex stimuli could not simply be predicted from local diplopia thresholds within the stimulated part of the visual field. These results, together with similar findings by Kertesz (1972), suggested the occurrence of a global adjustment of local diplopia thresholds. The initial purpose of the present study was to analyse this adjustment by determining diplopia thresholds for a variety of stimuli using as many different types of disparities as possible.

It was discovered during the first two months of this study that the apparent global adjustment of local diplopia thresholds for complex stimuli should not be ascribed to sensory processes but to the occurrence of vergence eye-movements minimizing overall disparities (*cf.* Chapter 4.2). At about the same time, Kertesz and Sullivan (1978) published data which conclusively showed that Kertesz's above-mentioned findings ahould also be ascribed to the occurrence of vergence eye-movements.

When these new data were brought to bear on analysis of the available data on diplopia thresholds in the literature, it was found that the diplopia thresholds for complex stimuli during normal binocular observation can always be predicted simply from local diplopia thresholds within the stimulated part of the visual field. No evidence remained to support the idea of a global sensory adjustment of local diplopia thresholds within the part of the visual field stimulated by a complex stimulus. It was, therefore, decided to switch the research to binocular single vision as described above, in order to throw light on problems that were more meaningful given the knowledge available then in the literature.

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II

TOWARDS AN UNDERSTANDING OF THE SENSORY PROCESSES UNDERLYING BINOCULAR SINGLE VISION

Chapter II deals with an unresolved controversy in the literature when the present study was started. This controversy concerned the nature of the sensory processes underlying binocular single vision. A major traditional view is that these sensory processes are a fusion mechanism eliminating the discrepancies between the images on the retinae of the two eyes (the 'retinal' disparities). According to the opposing view there is no such fusion mechanism.
Three studies were performed in connection with this controversy. In the first study the magnitude and nature of the diplopia threshold, that is, the value of the retinal disparity at which binocular single vision ends, have been investigated. In the second study the effect of stimulus presentation time on detection and diplopia thresholds for vertical disparities has been determined in order to find out whether the processing is aimed at eliminating or revealing these disparities. In the third study the detectability of differences between two different vertical disparities has been determined as a function of the reference disparity in order to find out whether this detectability is so much worse around zero disparity (where binocular single vision occurs) than at comparatively large reference disparities (where diplopia occurs) that it has to be assumed that there is a disparity-eliminating process operating around zero disparity.

2.1 What is the diplopia threshold?

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The magnitude and nature of the diplopia threshold, that is, the value of the retinal disparity at which binocular single vision ends, were studied in four experiments. The results show that the magnitude of the diplopia threshold is highly dependent on the subject tested (differences up to a factor of 6), the amount of training the subject has received (differences up to a factor of 2.5), the criterion used for diplopia (limits for unequivocal singleness of vision were up to a factor of 3 lower than those for unequivocal doubleness of vision), and the conspicuousness of disparity that can be influenced both by the surrounding stimuli (differences up to a factor of 3.5) and stereoscopic depth (differences up to a factor of 4.5). Our data do not confirm previous findings of interference effects associated with the initial appearance of binocular disparity when test stimuli are presented tachistoscopically. A remarkable finding was that the magnitude of the diplopia threshold seems to be determined by the amount of intrinsic noise in the disparity domain, as revealed by the standard deviations of the thresholds for tachistoscopically presented test stimuli. The overall results suggest that the diplopia threshold is, in essence, not the rigid boundary of a dead zone, but, rather, a disparity level corresponding to a lenient criterion for singleness of vision which leads to *useful* interpretation of the percept of the stimulus without disparity, given the variability of this percept due to intrinsic noise in the disparity domain.

An important aspect of human binocular vision is that a single visual percept can be obtained from two monocular images. This singleness of vision is accomplished by motoric alignment of the eyes so as to minimize the overall retinal disparity between the two monocular images and sensory integration of residual disparities. The sensory integration—usually called binocular fusion—can occur only when the residual retinal disparities between the two monocular images remain within certain limits.

Binocular fusion of parts of the images with horizontal disparity occurs practically *without loss of disparity information*, since only very small horizontal disparities ($\ll 1'$)[1] do not give rise to a sensation of depth. Binocular fusion of image parts with vertical disparity, on the other hand, is usually assumed to result in a loss of disparity information, because no *systematic* perceptual change analogous to depth has yet been reported.[2]

This study is concerned with the diplopia threshold, that is, the largest value of the retinal disparity that does not disrupt binocular single vision.

Measured values of the diplopia threshold quoted in the literature have little or no utility, due to the enormous variation between the results reported by different authors. Reported diplopia thresholds have ranged from 2′ to 20′ for horizontal disparity in the fovea, from 3′ to 16′ for vertical disparity in the fovea, and from 1.4° to 7° for cyclodisparity (references will be given below). The situation is much the same for diplopia thresholds in the periphery of the visual field. For instance, at an eccentricity of 4°-5°, diplopia thresholds from 4′ to 100′ have been reported (Crone & Leuridan, 1973). Moreover, the smallest reported thresholds are so low that they can be accounted for by monocular acuity, so that it is not even necessary to assume the existence of binocular fusion (see, e.g., Kaufman & Arditi, 1976a, 1976b). It is, therefore, of practical, as well as fundamental, importance to unravel the causes of this large variability in the size of the reported diplopia thresholds.

The purpose of the present investigation was to study the diplopia thresholds for vertical and horizontal disparity by evaluation of the *criterion for binocular single vision.* We also evaluated (1) possible interference effects associated with initial appearance of binocular disparity when test stimuli are presented tachistoscopically, (2) difference in the conspicuousness of information about the presence of disparity, and (3) possible systematic difference between subjects.

We have found evidence that different authors used different criteria for binocular single vision. In Woo's (1974) study, the criterion is likely to have been a perceptual change in the singleness of the line (e.g., broadening), as the reported diplopia thresholds (1.8′

We would like to thank G. J. van der Wildt, A. E. H. Peters, and Ch. M. M. de Weert for helpful discussions, and C. J. Keemink and J. B. P. van Deursen for their technical assistance. This investigation was supported by the Netherlands Organization for the Advancement of Pure Research (ZWO). Requests for reprints may be sent to A. L. Duwaer, Department of Biological and Medical Physics, Erasmus University Rotterdam, P.O. Box 1738, 3000 DR Rotterdam, The Netherlands.

-2.0′ for a vertical line with horizontal disparity presented in the fovea for 100 msec) are not even large enough to compensate for the specified line width (2.1′). The same holds true for the small thresholds that can be inferred from the data of Kaufman and Arditi (1976b): 1.4°-1.6° cyclodisparity in horizontal lines 2° long (corresponding to 1.5′-1.8′ vertical disparity at 1° eccentricity) is detectable (d′ = .61-2.11). Kaufman and Arditi determined the detectability of disparities, taking any changes in the appearance of the binocular image into account. On the other hand, when the transition from singleness to doubleness of vision is stressed for determination of the threshold, much larger diplopia thresholds are found (Mitchell, 1966: 6.8′-11.5′ for horizontal disparity and 4.5′-8.0′ for vertical disparity; Crone & Leuridan, 1973: 9′-20′ for horizontal disparity and 5′-16′ for vertical disparity, values estimated from the author's graphs; Sheedy & Fry, 1979: 5′-6′ for vertical disparity; Kertesz, 1973, and Kertesz & Sullivan, 1976: 4°-7° cyclodisparity for horizontal lines 2° long, which yields vertical disparities of 4.2′-7.4′ at 1° eccentricity). The data of Sheedy and Fry are interesting because they reveal shifts of the binocular images by .25′ to 1.4′ (mean value .8′) for a vertical disparity of 4′, which is less than their reported diplopia threshold. Since the mean 50% detection threshold for shifts under the particular stimulus condition amounted to about .35′ (estimated from the specified mean width of the psychometric curves), Sheedy and Fry would have reported lower diplopia thresholds if they, like Kaufman and Arditi (1976b), had used detectability of disparity as the criterion for diplopia. For a proper interpretation of diplopia thresholds, it seems, therefore, necessary to discriminate carefully between at least two "thresholds": on the one hand, a threshold reflecting the ability to recognize a stimulus with retinal disparity (which we shall call the "singleness limit" from now on) and, on the other hand, the more commonly used threshold for the perception of two separate images (called the "doubleness threshold" below). Both thresholds were determined in our study.

Kertesz and Sullivan (1976) argued that diplopia thresholds for tachistoscopically presented disparities will be smaller than those for continuously presented disparities because of interference by the initial appearance of binocular disparity. This "initial appearance cue" is assumed to be caused by the slowness of binocular fusion, as a result of which the visibility of the disparity is not reduced immediately. If this is indeed the case, *most recent data* on the diplopia threshold *will be affected by this cue*, as nearly all recent work in this field has been done with tachistoscopically presented stimuli. We judged this question to be important enough to deserve investigation, and therefore determined the singleness limits and doubleness thresholds for both tachistoscopically and continuously presented test stimuli with disparity. In the case of continuously presented test stimuli, the disparity level was slowly changed, in order to avoid such transient effects as the initial appearance cue.

Kertesz and Sullivan (1976) also argued against the use of stimuli with conspicuous monocular cues about the presence of disparity, as used, for example, by Kaufman and Arditi (1976b). These conspicuous monocular cues are claimed to reduce the measured diplopia thresholds. We investigated this effect by using three different fixation markers giving monocular cues with different levels of conspicuousness.

GENERAL METHODS

Stimulator

The stimuli were presented in an electronic stereoscope consisting of a white background screen (diameter 15°, mean luminance level of 3 cd/m²) and two XYZ displays (Philips PM3233 oscilloscopes with green P31 phosphor in Experiment 1 and HP1321A displays with white P31 phosphor in Experiments 2, 3, and 4). The displays were viewed dichoptically through two beam splitters, positioned directly in front of the subject's eyes and adjusted so as to present the two displays in the same direction at a fixation distance of 105 cm. The luminance of the (line) stimuli on the displays was adjusted to 1.8 log units above the (contrast) threshold for the perception of the stimulus. The widths of the stimuli were .3 mm (1.0′) for the Philips display and .35 mm (1.2′) for the HP1321A display.[3] The angular dimensions of the images on the two displays were equalized to within an accuracy of .3′ when being looked at through a telescope (magnification 30). The parameter in the experiments was the disparity between certain parts of the stimuli on the display screens. The level of the disparity had an accuracy of 0.1′ and was controlled by a microprocessor and an 8-bit digital-to-analog convertor. The alignment and identity of the stimuli were checked with the telescope before and after each experimental session.

Psychophysical Measuring Procedures

Most of the results presented below were based on a "three-alternative classification" of the test stimulus, but some data were gathered by a "two-alternative forced-choice" method. We shall now describe these two approaches in turn.

Three-Alternative Classification (see Figure 1)

Our three-alternative classification is an extension of the two-alternative classification, widely used in this field, in which the

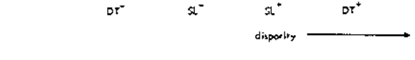

Figure 1. Schematic representation of the frequency of seeing (FOS) unequivocal singleness (1) and unequivocal doubleness (2) as a function of the disparity level in a classification procedure with neither unequivocal singleness nor unequivocal doubleness as the third alternative (?).

subject is only allowed to answer "single" or "double." We found that these categories were not adequate because of the occurrence of transitional percepts between singleness and doubleness.

Our first alternative, "(1)," was an unequivocal single image which was defined as the "internal representation of the percept of the stimulus *without* disparity" (a sharp line, not broadened, not "restless," and perceived by both eyes). This internal representation was built up by familiarizing the subject with the percept of the stimulus without disparity. The second alternative, "(2)," was an unequivocal double image which was defined as the percept of two lines (with a separation). When the percept was neither unequivocally single nor unequivocally double, the subject was asked to select the third alternative, "(?)," and to describe the transitional percept afterwards. The disparity level above which an unequivocally single image is no longer seen determines the threshold for a perceived deviation from the internal representation of the percept of the stimulus without disparity. We shall refer to this threshold as the *singleness limit* (SL) from now on. The disparity level above which unequivocally double images are seen will be called the *doubleness threshold* (DT). The subjects were asked to classify in this way the percepts evoked by tachistoscopically presented test stimuli and by continuously visible test stimuli.

Tachistoscopic presentation. In the case of tachistoscopic presentation, the subject initiated presentation of the test stimulus by pressing a button. The stimulus was then presented with a constant disparity, selected at random by a microprocessor from 12 preselected values covering a sufficiently wide range to evoke all possible percepts. The subject then classified the percept. The subject was instructed to look at the fixation marker with close attention for at least 2-3 sec between successive stimulus presentations. In each session, the subject had to classify the percepts evoked by the 12 disparity values 20 times each. After that, the session was repeated at least once again with 12 interpolated disparity values, until a frequency-of-seeing (FOS) curve was obtained for each of the three image classes in which each transition from 0 to 1 was based either on at least four different points, each point based on at least 20 observations, or on the maximum number of points given the available resolution of .33′.

Continuous presentation. The procedure was different for *continuous observation* of the test stimulus. Here each run was started by the subject with the aid of a switch. Two to 5 sec later, the disparity slowly changed in steps of .33′, .66′, or 1.32′. The disparity started at a preselected positive value and then decreased through zero to a preselected negative value or increased through zero from negative to positive. The subject was asked to keep a button pressed as long as the percept of the stimulus fell into the intermediate category ("?," i.e., neither unequivocal singleness nor unequivocal doubleness). At the end of each run, the subject was to indicate (by pressing the appropriate button) whether his/her attention had been diverted or the fixation marker had not remained unequivocally single during the run. If so, the data were automatically excluded from the subsequent analysis. The subject continued until 20 good runs were completed. The direction of the change in disparity was then reversed, and another series was begun. The recordings were used to construct FOS curves for each of the three image classes.

Calculation of thresholds. The FOS curves obtained were fitted by a convolution of normalized Gaussian noise and hypothetical regions of disparity in which one of the three image classes is always seen. Each abrupt transiton between neighboring regions was defined to be a "threshold" with the standard deviation of the Gaussian noise as its standard deviation. This implies that the thresholds were calculated under the assumption that, at each disparity, one of the three percepts was always seen, but that the effective locations of the transitions between the percepts varied due to intrinsic additive Gaussian noise. All thresholds and standard deviations are means of the values found at positive and negative disparities. The data for continuous presentation of the test stimulus were also averaged over the values obtained with increasing and decreasing disparity.

Table 1
Details of the Subjects

Subject	Age	Sex	Optical Correction		Visual Acuity		
			L	R	L	R	S
A.L.D.	25	M	S- .75	S- .75	5/4	5/4	15″
C.J.K.	38	M			5/4	5/4	30″
B.D.L.	32	M	S-3.25	S- 3.00	5/4	5/4	30″
A.E.H.P.	25	F	S-4.75*	S- 4.75*	5/4	5/4	15″
T.H.S.	27	M	S-7.00	S- 7.00*	5/4	5/4	60″
C.J.D.	19	M	S-9.00	S-11.00	5/4	5/4	30″

Note—L = left, R = right, S = stereo. Visual acuity was determined with the aid of the Landolt-C chart. Stereo acuity (in seconds) was tested with the TNO test based on random-dot patterns in anagliph form (Lameris, Utrecht, The Netherlands). Optical correction is expressed in diopters. **These subjects also viewed through an artificial pupil of diameter 2.5 mm.*

Two-Alternative Forced Choice

In this method, each trial was started by the subject's pressing a button. The test stimulus was then presented twice: first .5 sec after initiation and then 3 sec after initiation. In one of the two presentation intervals, the test stimulus contained a disparity; in the other, it did not. The subject was asked to decide which interval contained the disparity. The correct answers for 50-100 trials were accumulated. At least three different disparity values were used to determine the disparity level producing 75% correct answers (which corresponds to a detection level of 50%). This value will be called the "detection threshold." The detection-threshold data presented below are means of the values obtained at positive and negative disparity.

Experimental Procedure

The subject was aligned in the test setup and provided (if necessary) with optical correction in order to achieve optimum sharpness of the perceived stimulus. The subject's head was fixed by using a bite-board. The luminance level of the stimuli on the screens was adjusted to 1.8 log units above the threshold for perception of the stimulus. The subject was then informed of the experimental procedure described above, and was allowed ample time to look at the various stimuli and to familiarize him- or herself with the associated percepts. The experiments were then run as described in detail above. The subjects were asked to take a rest when they felt tired or when the sharpness of the perceived image deteriorated. The constancy of each subject's performance was monitored during collection of threshold data. When, by visual inspection of the FOS curves obtained, an apparent threshold shift was noticed, the preceding part of the experiment was repeated until no further shift was apparent. Threshold shifts occurred mainly during the first few experimental sessions for each subject.

Subjects

Six subjects participated in the various experiments (see Table 1). Only Subject A.L.D.—one of the authors—was aware of the purpose of the experiments. All but one had to be corrected optically to achieve optimum sharpness of the perceived stimulus. In order to obtain long-term stability for optimum sharpness, artificial pupils (diameter, 2.5 mm) had to be used with two subjects (Subjects A.E.H.P. and T.H.S.).

EXPERIMENT 1: THRESHOLDS FOR VERTICAL DISPARITY

Method

Stimuli

The stimuli used in this experiment are depicted in Figure 2. They were presented in the middle of a white background screen,

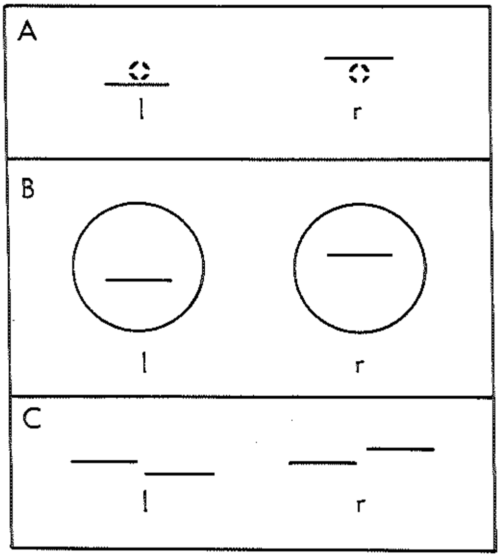

Figure 2. Schematic respresentation of the stimuli used in Experiment 1. The letters l and r stand for presentation to the left and right eye, respectively. The broken line used to represent the 5′ fixation circle means that this marker disappears during the course of each trial before presentation of the stimulus.

on which the vertical orientation was marked by means of a black line (width 1.0′) with a gap 1.5° wide in the middle, where the stimuli were presented. The stimuli on the display screen consisted of a fixation marker and a test stimulus.

Fixation markers. The fixation circle shown in Figure 2A, indicated by "[O]" from now on, had a diameter of 5′. The subjects were instructed to look at the middle of the circle, while waiting for the test stimulus. The circle disappeared 200 msec before the test stimulus appeared and reappeared .6 sec after the test stimulus had vanished. This fixation marker can be regarded as giving highly inconspicuous cues concerning monocular displacements.

The fixation circle of Figure 2B (indicated by "O") had a diameter of 1° and was continuously visible. With tachistoscopic presentation of the test stimulus, the subjects were instructed to look at the center of the circle. With continuous presentation of the test stimulus, the subjects were instructed to look alternately at the upper and lower halves of the circle, switching their gaze regularly to avoid fading of the test lines. This fixation marker may be regarded as giving monocular disparity cues of intermediate conspicuousness.

The left-hand line in Figure 2C was the third fixation marker (indicated by "–"). It was also continuously visible. It had a length of 30′ and was laterally separated from the test line by 3′. The subjects were instructed to look at the right-hand part of this marker, switching their gaze regularly from this part to the middle, when the test stimulus was continuously visible. This marker provides a highly conspicuous cue for monocular displacements.

Test stimulus. The test stimulus was a pair of dichoptic horizontal lines with a length of 30′, a width of 1.0′, and a variable vertical disparity.

When the test stimulus was presented tachistoscopically, the presentation time was 200 msec. (Such test stimuli are simply called "200 msec" from now on.) This presentation time is a compromise between allowing as much time as possible for fusion to develop, on the one hand, and preventing a raising of disparity thresholds by the interference of fusional eye movements, on the other. Experimentally, this raising was found not to occur for presentation times up to at least 200 msec. This agrees with data in the literature on reaction times of fusional eye movements. Fusional eye movements in the horizontal direction start after about .2 sec (Mitchell, 1970). A presentation time of about 200 msec has the further advantage of providing a relatively familiar stimulus form: Large vertical foveal disparities are likely to be present for at least the reaction time of fusional eye movements in daily life.

When the test stimulus was presented continuously, the vertical disparity changed in steps of .33′ at intervals of 800 msec, that is, at a rate of .4′/sec (such stimuli are called ".4′ sec^{-1}" or ".4 arc min/sec"). The interference of fusional eye movements was minimized by foveal fixation of the marker. When fusional eye movements did, nevertheless, occur during the run, the subject could perceive this from the change that occurred in the appearance of the fixation marker, which did not remain single and usually became unequivocally double. Runs in which fusional eye movements were noticed were disregarded.

Measuring Procedure

The psychophysical measuring procedure used was three-alternative classification.

Results

The disparity thresholds determined for the five subjects are presented in Table 2.

Table 2
Singleness Limits (SL) and Doubleness Thresholds (DT) With Their Standard Deviations (in Minutes of Arc) for Vertical Disparity in the Fovea

Subject	n	SL		T	DT	
		Mean	SD		Mean	SD
[0], 200 Msec						
C.J.K.	6	6.2	1.8	4	8.1	2.3
A.L.D.	5	3.1	1.1	1	4.7	.8
B.D.L.	8	4.3	.9	1	8.3	1.4
A.E.H.P.	7	6.4	2.7	4	7.7	1.8
T.H.S.	5	18.7	5.1	2a	29.8	7.7
0, 200 Msec						
C.J.K.	1	6.8	1.8	2b	8.4	2.1
	3	5.7	2.5	2b	7.6	1.6
A.L.D.	1	2.5	1.0	1	4.5	.8
	6	2.4	.8	1	4.1	.8
B.D.L.	2	6.3	1.5	1	11.2	1.6
	3	6.1	1.1	1	10.5	1.0
	5	5.5	1.8	1	10.4	1.0
A.E.H.P.	1	7.4	7.3	2a	20.0	3.0
	5	5.0	4.8	2a	12.3	2.1
	8	6.1	2.7	4	8.5	2.3
T.H.S.	2	12.8	7.2	2a	25.8	4.4
——, 200 Msec						
C.J.K.	4	4.2	2.5	2b	6.2	2.2
A.L.D.	3	1.2	.8	1	4.0	1.1
	7	1.3	.6	1	3.0	.6
B.D.L.	4	4.5	1.2	1	9.2	1.1
	7	2.5	1.7	1	6.8	1.3
A.E.H.P.	3	3.4	1.6	2a	11.2	2.9
	9	3.7	1.8	2a	7.2	2.7
T.H.S.	3	5.4	3.4	2a	19.8	3.4

Table 2 (continued)

Subject	n	SL		T	DT	
		Mean	SD		Mean	SD
				0, .4 Arc Min/Sec		
C.J.K.	2	3.0	.6	1/3*	6.5	.8
A.L.D.	2	4.0	.6	1	6.9	.9
	9	1.9	.5	1	4.5	.5
B.D.L.	1	4.3	.8	1	8.0	.7
A.E.H.P.	2	7.7	2.2	3	17.0	2.1
	6	6.4	1.2	3	12.8	2.0
	10	4.4	1.4	1	8.8	1.8
T.H.S.	1	8.0	1.3	2a/3†	17.0	3.3
				—, .4 Arc Min/Sec		
C.J.K.	5	2.8	.7	1/3*	7.2	1.6
A.L.D.	4	1.9	.4	1	3.9	.5
	8	1.2	.3	1	3.5	.5
B.D.L.	6	3.1	.6	1	7.0	.6
A.E.H.P.	4	4.0	1.4	3	12.0	2.5
	11	3.4	1.4	3	9.1	1.6
T.H.S.	4	5.8	1.8	2a/3†	17.9	2.8

*Note—T = transitional percept: (1) broadened, blurred, restless image; (2) displaced single image, (a) image of right eye, (b) image of left eye; (3) rivalry between the images in the left and right eyes; (4) subject not able to specify the transitional percept. n = session number. *Near SL = 1; near DT = 3. †For positive vertical disparity (image in right eye up, left eye down) and for negative disparities (right eye down, left eye up) near SL = 2a; for negative disparities near DT = 3.*

The singleness limits were found to vary between 1.2′ and 19′, and the doubleness thresholds between 3.0′ and 30′. Taken together, the range found is in good agreement with the overall range of diplopia thresholds reported by other authors (see the introduction).

The following, more detailed analysis is based upon the thresholds obtained in the last session of each experiment, when the subjects had reached stable performance. These thresholds are presented in Figure 4.[4] One of the subjects took a lot of experimental time to reach a stable performance. As shown in Figure 3, the thresholds decreased by up to 11.5′ (a factor of 2.3) from the start of the experiments to the end. The occurrence of this training effect has been both reported (see, e.g., Ogle, 1964) and denied (see, e.g., Mitchell, 1966) in the literature.

Differences Between Subjects

Inspection of Figure 4 reveals that differences between subjects are the most important cause of the large range of observed disparity thresholds.

It should be borne in mind that a large interindividual variability for a sensory threshold as such is not a surprising result, given the known interindividual variability of up to 1 order of magnitude for detection thresholds of, for example, the auditory system (Dadson & King, 1952) and the vestibular system (Clark & Stewart, 1969).

The interindividual variability is also reflected in the standard deviations of the thresholds. When the thresholds are expressed in standard-deviation units, the variability is reduced[5] (see Figure 4). *This implies that the interindividual relevance of this signal-to-noise ratio of the threshold is greater than that of the threshold itself.* An important theoretical implication of this finding will be discussed below (see Summary and Conclusions of this section).

One of the possible factors underlying the enormous differences between the subjects seems to be the optical correction applied. In Figure 5, the disparity thresholds obtained in the *first* session of each experiment are compared with the optimum optical correction. Inspection of this figure shows that the *initial* threshold—especially the doubleness threshold—is higher when the optimum correction is larger. This can be made plausible in several ways.

One might argue that this dependency on optimum optical correction originates from the angular reduction of the retinal images that *may* occur in corrected myopes. This angular reduction does not occur when the need for optical correction is caused only by an elongated eye, but it does occur when the refractive power of the eye is too large (Ogle, 1971). Although we did not establish the nature of the myopias (so they might have had a refractive origin), we can still exclude angular reduction of the retinal images as the major cause of the higher thresholds at larger optimum optical corrections, because: (1) training may reduce the thresholds of subjects with large optimum optical corrections (see Figure 3); (2) the dependency on optimum correction should then be the same for all thresholds, which is not the case; and (3) the maximum effect of this angular reduction is comparatively small. A psychophysical experiment showed that a change of the effective refractive power of the eye by addition of a correction lens results in a perceived angular reduction of only 2.2% per diopter for the spectacles used. This implies that the actual disparity thresholds may be smaller by, at most, 0% for 0 d, 1.7% for −.75 d, 6.9% for −3.15 d, 10.5% for −4.75 d, and 15.4% for −7 d.

It is more likely that the dependency of the thresholds on the optimum optical correction reflects adaptation to vertical disparities in daily life as a result of small rotations in the frontal plane of an observer's spectacles.

Another cause of the interindividual variability of disparity thresholds, may be systematic differences in the accuracy of the alignment of the eyes. Our study on this was reported in Duwaer and van den Brink (Note 1).

The Criterion for Diplopia

The geometric means of the singleness limits are a factor of 1.5 to 2.6 less than the geometric means of the doubleness thresholds.

The differences are especially large for continuous presentation of the test stimulus and for tachistoscopic presentation in combination with the fixation line. A

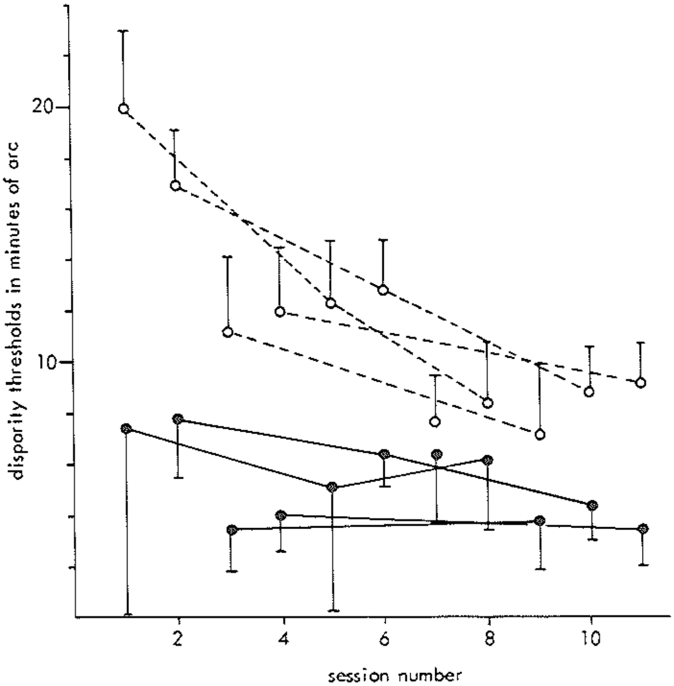

Figure 3. Disparity thresholds as a function of session number for Subject A.E.H.P. The singleness limits are represented by solid circles, and the doubleness thresholds, by open circles. The lines connect disparity thresholds determined under the same stimulus conditions, as given in Table 2. The lengths of the vertical bars are equal to the standard deviations.

discrimination between singleness limit and doubleness threshold would thus be at least of practical utility apart from any theoretical light it might throw on these matters.

All transitional percepts between unequivocal singleness and unequivocal doubleness seem to indicate partial elimination of disparity information by partial fusion or suppression (see Table 2). This implies that binocular single vision starts to deteriorate at the singleness limits, that is, well below the doubleness threshold.

Conspicuousness of the Disparity

When the test stimulus is presented in combination with the fixation line providing a highly conspicuous monocular displacement cue, the observed singleness limits fall. The same effect, but less marked, is found for the doubleness thresholds, but only when the test stimulus is presented tachistoscopically.

A major cause of this effect is a sharpening of the diplopia criterion. This can be seen from the fact that the signal-to-noise ratios also decrease when the fixation line, rather than one of the fixation circles (see Figure 4), is used.

It should be noted that the effect of the fixation line on the disparity thresholds need not necessarily be due to increased conspicuousness of the monocular displacements as such. It can also be caused by increased conspicuousness of the disparity due to greater variation of the disparity per unit of visual angle (higher disparity gradient). It should be borne in mind that a high disparity gradient with unnoticeable monocular displacements can be realized with the aid of random-dot stereograms.

The Initial Appearance Cue

Transient effects, such as an initial appearance cue, that may occur with tachistoscopically presented stimuli are avoided when the test stimulus is continuously visible and the disparity is slowly changing. In spite of the lack of this initial appearance cue, we found that the disparity thresholds do *not* rise, but actually tend to fall when the test stimulus is presented continuously. The relevance of the initial

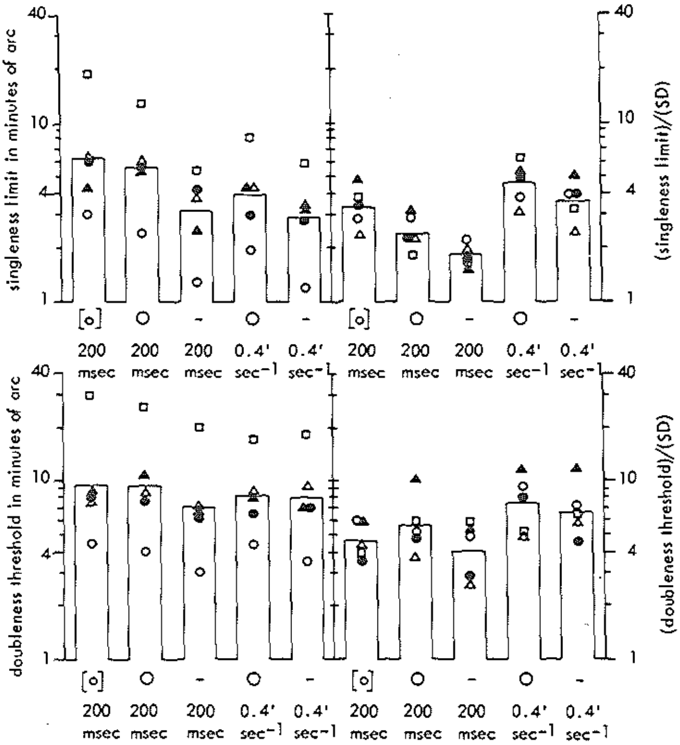

Figure 4. Disparity thresholds in minutes of arc (left part of the figure) and in standard-deviation units (right part of the figure) for the five different stimulus conditions. The thresholds in the upper part of the figure are the singleness limits. The doubleness thresholds are plotted in the lower part of the figure. Each type of symbol represents one of the five subjects. The height of the bars indicates the geometric mean of the thresholds.

appearance of binocular vertical disparity in tachistoscopically presented test stimuli may, therefore, be doubted. This conclusion is in agreement with that of Arditi and Kaufman (1978), who prevented interference effects due to an initial appearance cue by gradually increasing the intensity of their tachistoscopically presented test stimuli from below the perception limit.

Summary and Conclusions

The accuracy with which a disparity threshold can be determined, that is, its standard deviation, seems to have an important bearing on whether or not singleness of binocular vision is achieved.

The standard deviations obtained with tachistoscopic presentation of test stimuli of constant disparity can be interpreted as reflecting standard deviations of intrinsic noise in the disparity domain, because the internal representations of test stimuli of different disparities are built up independently. This is not the case for continuous presentation of test stimuli with a slow increase or decrease in disparity. Comparison of these standard deviations with the corresponding thresholds suggests that a diplopia threshold is set by a criterion that depends on the amount of intrinsic noise in the disparity domain.

Subjects tend to use a lenient criterion for the singleness limit, most probably because the disparity information is not very conspicuous. However, the criterion used becomes sharper when the disparity information is made more conspicuous.

Binocular single vision starts to deteriorate at a disparity level (the singleness limit) that may be much lower than the level where this deterioration is completed (i.e., the doubleness threshold) and unequivocal binocular double vision is established.

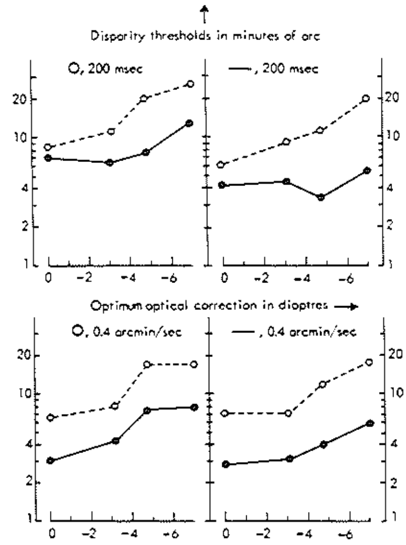

Figure 5. Singleness limits (solid circles) and doubleness thresholds (open circles) as functions of the optimum optical correction. The thresholds were determined in the first session performed under the particular stimulus conditions for each subject. The data for Subject A.L.D. (spherical correction of −.75 diopter) are omitted because his first sessions were preceded by a long period of observing foveal vertical disparity in a large number of pilot experiments.

It seems doubtful whether the initial appearance of binocular vertical disparity for tachistoscopically presented test stimuli lowers the diplopia threshold.

EXPERIMENT 2: THRESHOLDS FOR VERTICAL DISPARITY OUTSIDE THE FOVEA

In order to test the apparent importance of intrinsic noise in the disparity domain, we now compared thresholds for vertical disparity in the fovea with those outside the fovea, where this noise will be substantially larger.

Method

Stimuli

The stimuli consisted of a fixation marker, a test stimulus (both 1.8 log units above the perception threshold) and a white background (15° × 15°; mean luminance level 3 cd/m^2).

Fixation marker. All fixation markers used consisted of three concentric squares of side 1°, 1.2°, or 1.4° and a vertical or horizontal line 10° long (see Figure 6). For the determination of foveal thresholds, a gap was left in the central 1.4° of the line. For the determination of thresholds outside the fovea, a line 20′ long perpendicular to the longer line was added in the center to form a fixation cross.

During the determination of thresholds for horizontal test lines with vertical disparity, each subject was instructed to fix his gaze on the middle of the fixation marker, in the case of tachistoscopic presentation, and alternately on the upper and lower sides of the smallest square, in the case of continuous presentation. The fixation position had to be varied in the case of continuous presentation in order to prevent fading of the test lines.

Test stimulus. The test stimuli were presented at the center of the fixation marker (Figure 6a), 4.5° to the right of the center (Figure 6b), or 4.5° above the center (Figure 6c).

The foveal test stimulus was 30′ long, and the peripheral test stimulus, 110′ long. According to the data of Drasdo (1977), these lines will stimulate about the same "length" in the visual cortex.

The test stimuli were presented either tachistoscopically, with a presentation time of 160 msec, or continuously while the disparity slowly changed at a rate of .4′/sec in the fovea or .8′/sec at an eccentricity of 4.5°.

Measuring Procedure

The psychophysical measuring procedure used was three-alternative classification.

Results

Experiment 2 was performed by two subjects with a large difference in optimum optical corrections. Both subjects found it much less obvious to classify the percept evoked by the tachistoscopically presented test stimuli as "single" in the periphery of the visual field than in the fovea. Singleness, as such, had no meaning in the visual periphery, since the percept was only rarely perceived as single according to foveal standards. The classification "unequivocal single" should therefore not be interpreted too literally. It simply meant "perception of the stimulus without

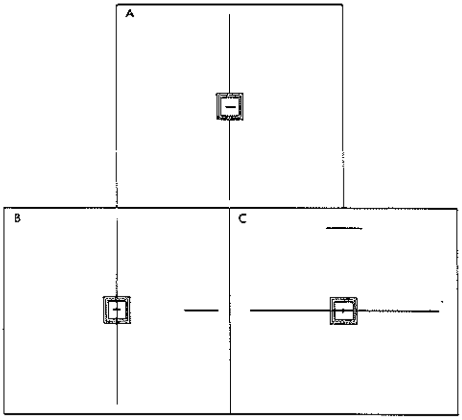

Figure 6. Schematic representation of the stimuli in Experiments 2 and 3. The test stimulus was the horizontal line in the middle of the squares in A, to the right of the squares in B, and above the squares in C. The remaining part of each stimulus served as a fixation marker. For Experiment 4, the stimuli in A and C were rotated clockwise through 90°, and the stimulus in B, counterclockwise through 90°.

disparity." Subject A.L.D. noticed that when the test stimulus was presented tachistoscopically without disparity, the percept varied between single and double according to the foveal standards.[6] Being a highly skilled observer, Subject A.L.D. was able to apply the criteria "very good single," "single" (i.e., the ensemble of percepts evoked by the stimulus without disparity), and "not unequivocally double" consistently. The FOS curves obtained with the aid of these criteria are given in Figure 7A. When these curves are fitted by a convolution of normalized Gaussian noise and a range of disparities in which the percept in question is always seen, a remarkable result emerges. The limits of the above-mentioned ranges, the "thresholds," can vary between 3′ and 16′, while the accuracy with which these limits are determined changes much less (see Figure 7B). *What is important here is this accuracy, that is, the amount of noise in the disparity domain.* The classification "single" and "unequivocal double" are just two possible criteria on an apparently continuous scale. It also becomes evident why the singleness limit is roughly equal to twice its standard deviation. This standard deviation should be interpreted as reflecting the intrinsic noise in the disparity domain. As a result of this noise, a stimulus without disparity will result in an internal representation with an effective disparity of up to about 2-3 times the standard deviation of the noise. Apparently, the subjects "choose" their criterion for unequivocal singleness at this disparity level.

The data also indicate that binocular singleness or doubleness is determined by absolute retinal disparities and not by relative disparities in the stimulus. This may be concluded from the finding that optimum singleness (the center of the region of unequivocal singleness) was located at the nonzero stimulus disparities (+12′ for Subject C.J.D. and −4′ for Subject A.L.D.) that compensated as well as possible the retinal disparities introduced by the cyclophorias of 2.5° extorsion in Subject C.J.D. and .8° intorsion in Subject A.L.D.[7] Because of the cyclophoria in Subject C.J.D., the effective disparity level of the

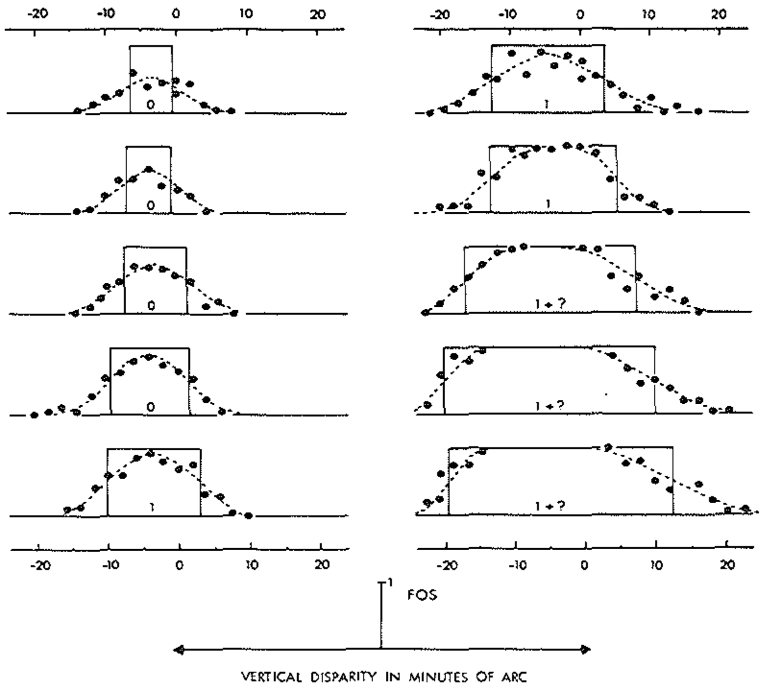

Figure 7A. Frequencies of seeing "very good single" images ("0," four sessions), "single" images ("1," i.e., the ensemble of percepts evoked by the stimulus without retinal disparity, three sessions), and "not unequivocally double" images ("1 + ?," three sessions), represented by solid circles, as functions of the vertical disparity in a tachistoscopically presented horizontal line located 4.5° to the right of the fixation point. These data were obtained for Subject A.L.D. Each experimental point was obtained from 20 trials. The asymmetries in the frequencies of seeing curves are caused by the cyclophoria in this subject (see text).

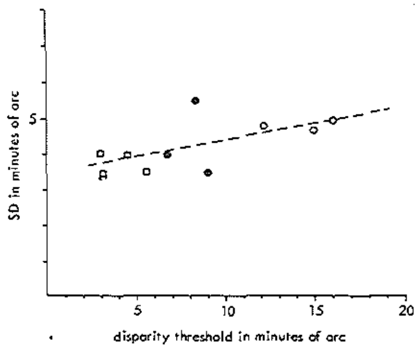

Figure 7B. The mean standard deviation of each "threshold" (the mean standard deviation of the distributions used to fit the experimental points in Figure 7A) are plotted as a function of the disparity threshold. The open squares represent "very good single" images, the solid circles, "single" images, and the open circles, "not unequivocally double" images. The dotted line is obtained by linear regression, with the standard deviation as dependent variable.

stimulus without disparity fell only just within the singleness limits!

The singleness limits and doubleness thresholds obtained are presented in Table 3.

At an eccentricity of 4.5°, the thresholds obtained vary between 6′ and 30′. This is appreciably less than the range reported in the literature, which extends up to 60′ (Crone & Leuridan, 1973). Our major finding is that, just as in the fovea, the signal-to-noise ratios of the singleness limits for tachistoscopic presentation of the test stimulus amount to about 2. The finding of a relatively constant signal-to-noise ratio for thresholds of different sizes thus seems to apply not only interindividually, but also intraindividually at different eccentricities.

Conclusions

The results of Experiment 2 confirm, and even reinforce, the importance of the amount of intrinsic noise in the disparity domain for the size of diplopia thresholds. It is, furthermore, evident that the singleness limits and doubleness thresholds are based on just two criteria on a continuous scale of possible criteria which even extends below the singleness limit.

The results also suggest that the singleness/doubleness disparity thresholds are determined by *absolute retinal* disparities and *not by relative* disparities in the stimulus as is, for example, the case for the detection threshold for horizontal disparity when detection is based on relative stereoscopic depth.

EXPERIMENT 3: DETECTABILITY OF VERTICAL DISPARITY

If even the singleness limit can be regarded as simply the result of applying a lenient criterion on a continuous scale of possible criteria, the detection threshold determined in a discrimination task that invites the subject to use the sharpest possible criterion should be below the singleness limit.[8] This was checked in Experiment 3.

Method

Stimuli

The stimuli were the same as those used as in Experiment 2. The test stimulus was only presented tachistoscopically, with a presentation time of 160 msec. The reference stimulus contained no retinal vertical disparity.

Measuring Procedure

The psychophysical measuring procedure used was two-alternative forced choice.

Results

Experiment 3 was performed with the same two subjects used in Experiment 2. The results are given in Table 4.

Inspection of Tables 3 and 4 shows that all detection thresholds are, indeed, smaller than the corresponding singleness limits. The most remarkable performance was that of Subject C.J.D., who was found to be capable of detecting a foveal vertical disparity of only 2.2′, although his singleness limit amounted to 7.0′ and his diplopia threshold to as much as 19′, under the same stimulus conditions. This subject reported that he discriminated between the stimuli on the basis of *minor differences in unequivocally single images*. These differences between successive presentations were smaller than the variation of the percept evoked by the test stimulus without disparity in a large number of successive presen-

Table 3
Singleness Limits (SL) and Doubleness Thresholds (DT) With Their Standard Deviations (in Minutes of Arc) for Vertical Disparity in the Fovea, 4.5° to the Right of the Fixation Point (4.5/0) and 4.5° Above the Fixation Point (4.5/90)

	Fovea								4.5/0								4.5/90							
	160 Msec				.4 Arc Min/Sec				160 Msec				.8 Arc Min/Sec				160 Msec				.8 Arc Min/Sec			
Sub-ject	SL		DT		SL		DT		SL		DT		SL		DT		SL		DT		SL		DT	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
A.L.D.	2.0	.7	3.6	.8	1.6	.5	4.7	.6	8.1	4.4	14.4	4.8	6.3	1.5	16.2	1.4	10.1	5.1	22.9	5.0	6.5	2.0	18.4	2.4
C.J.D.	7.0	4.4	19.3	2.5	3.6	1.3	13.0	2.0	16.9	7.7	29.3	6.4	9.6	3.9	19.7	3.8	19.0	7.8	27.6	4.8	14.0	3.0	23.6	3.2

Table 4
Detection Thresholds (in Minutes of Arc) for Vertical Disparity in the Fovea, 4.5° to the Right of the Fixation Point (4.5/0), and 4.5° Above the Fixation Point (4.5/90)

	160 Msec		
Subject	Fovea	4.5/0	4.5/90
A.L.D.	1.6	5.3	6.1
C.J.D.	2.2	14.1	14.5

tations, which had not been noticed until this test procedure was applied. It should be noted that the difference between Subjects A.L.D. and C.J.D. became negligible in this experiment as far as the detectability of foveal disparity was concerned. However, their impression of the stimulus just above the detection threshold differed substantially: Subject A.L.D. certainly did *not* perceive an unequivocal single line; instead, he saw a restless, blurred, broadened line. It is not unlikely that this difference is due to the higher intrinsic noise level in Subject C.J.D., as a result of which he may have been more accustomed to the occurrence of these intermediate disparities.

In analyzing the magnitude of the detection thresholds found for vertical disparities, it must be reminded that these thresholds have a lower limit determined by the amount of intrinsic noise in the disparity domain.[8] This lower limit is equal to .955 × the standard deviation of the intrinsic noise for the case of ideal signal detection without *any* loss of disparity information. Since both positive and negative vertical disparities result in a separation (without sign) of the test lines, it is not unlikely that information about the *sign* of the disparity is lost. Such a loss of sign information would raise the lower limit of the detection threshold to 1.49 × the standard deviation of the intrinsic noise. Comparison of the measured detection thresholds with lower limits predicted on the basis of the standard deviations of the singleness limit and doubleness threshold as estimates of the standard deviation of the intrinsic noise suggests that it is necessary to assume *some* loss of disparity information to explain these results. In the highly practiced subject, A.L.D., this loss of information can be almost entirely ascribed to loss of information about the *sign* of disparities (in itself, quite a likely effect). This makes it tempting to deny the existence of any *insurmountable* loss of information about the magnitude of vertical disparities, that is, the occurrence of dead zones or of irreducible Panum's fusional areas for vertical disparities.

Conclusion

The detection threshold for vertical disparity (determined by a two-alternative forced-choice procedure) is lower than the singleness limit and, of course, than the doubleness threshold (both determined by the three-alternative classification procedure above). This implies that neither the singleness limit nor the doubleness threshold can be interpreted as the boundary of a region of disparities in which the information about the size of disparity is lost. This agrees with similar results obtained by Kaufman and Arditi (1976b) for stimuli with cyclodisparity.

EXPERIMENT 4:
THRESHOLDS FOR HORIZONTAL DISPARITY

In a final experiment, we gathered some data on the magnitude of thresholds for horizontal disparity.

Method

Stimuli

The stimuli were the same as those of Experiment 2, except that they were rotated through 90° in the frontal plane (Figures 6A and 6C: clockwise rotation; Figure 6B: counterclockwise rotation). The foveal thresholds were determined while the subjects looked at the middle of the lower side of the smallest square in the case of tachistoscopic presentation and alternately at the left and right end of this side in the case of continuous presentation. The thresholds outside the fovea were determined while the subject fixed his gaze on the center of the fixation marker in the case of tachistoscopic presentation and alternately on the left and right sides of the smallest square in the case of continuous presentation. The fixation position had to be varied in the case of continuous presentation in order to prevent fading of the test lines.

Measuring Procedure

The psychophysical measuring procedures used were both three-alternative classification and two-alternative forced choice.

Results

Experiment 4 was performed with two subjects, both of whom were found to base the detection threshold for horizontal disparity on the perception of relative depth in an otherwise unequivocal single image.[9] These detection thresholds were much lower than those for vertical disparity. They amounted to .2′-.3′ in the fovea and to .8′-1.0′ at an eccentricity of 4.5°. These values are comparable to those obtained by other authors (e.g., Ogle, 1964).

When the horizontal disparity is further increased, the relative depth increases and, in addition, the appearance of the "single" percept, apart from its depth, changes. Both subjects characterized this change as a gradual increase in "glow," that is, diffuse irradiance, around the line. At an eccentricity of 4.5°, the line with glow eventually changes into one restless object of indeterminate appearance at an intermediate lateral position and with depth. At still larger disparities, the line becomes unequivocally double while the impression of depth strongly deteriorates. These descriptions are similar to those given by Ogle (1964), *if Ogle's* *"fused line" is interpreted as a line without a substantial amount of "glow."*

For determination of the singleness limits and doubleness thresholds, the subjects were instructed to disregard the complicating occurrence of depth and to concentrate on the appearance of the line perpendicular to the line of sight. The results are presented in Table 5.

The foveal disparity thresholds vary between 4′ and 22′.[10] This covers a substantial part of the range of values reported in the literature (see the introduction). The same can be said of the thresholds at an eccentricity of 4.5°, for which values between 13′ and 135′ were obtained. The differences between the two subjects become smaller when the thresholds are expressed in standard-deviation units and when the test line is continuously visible while the disparity slowly changes.

Conclusions

For horizontal disparities, disparity thresholds can be obtained that can vary by up to two orders of magnitude (in the fovea: .25′-22.2′; at an eccentricity of 4.5°, 1′-135′). The detection thresholds found here are markedly lower than those for vertical disparity. The singleness limits and doubleness thresholds, on the other hand, are higher than those for vertical disparity. The latter is not surprising, since, because of the accompanying occurrence of stereoscopic depth, deviations from singleness as a result of horizontal disparity are much less conspicuous.

DISCUSSION

Which Threshold is the Diplopia Threshold?

The singleness limits and doubleness thresholds, especially in the fovea, occur at disparity levels at which the *interpretation* of the binocular percept in terms of singleness and doubleness undergoes its two major changes. The singleness limit specifies the disparity level at which the perceived singleness of the stimulus starts to deteriorate, and the doubleness threshold marks the disparity level at which this deterioration is completed. The singleness limit and the doubleness threshold should thus be regarded as lower and upper limits of "the" diplopia threshold.

Although the detection thresholds are of major theoretical importance in the evaluation of the nature of the diplopia threshold, they have little or no utility as diplopia thresholds. The detection threshold for horizontal disparity is not at all useful as a diplopia threshold, because it is based on differences in depth in otherwise unequivocal single images, although there is evidence that this depth cue differs *essentially* from the singleness doubleness cue: Depth is based on a processing of *relative* disparities in the stimulus (disparity gradients; Duwaer & van den Brink, Note 1), whereas the results of our Experiment 2 suggest that the singleness/doubleness cue is determined by *absolute* retinal disparities. The detection threshold for vertical disparity—though most probably based on a cue that does *not* differ essentially from the singleness/doubleness cue— is not so useful as a practical diplopia threshold because it specifies the performance of disparity detection in a discrimination task that is optimum for this purpose without considering the singleness of binocular vision as such.

What Determines the Magnitude of the Diplopia Threshold?

Our results suggest that an important determinant of the magnitude of the diplopia threshold is the amount of *intrinsic noise in the disparity domain.* When there is more noise, for example, outside the fovea or in some other subject, the diplopia threshold is higher.

The magnitude of the diplopia threshold also depends on the *conspicuousness of changes in singleness due to the disparity.* When these changes are made more conspicuous, for example, by the use of a fixation marker to make monocular displacements much more noticeable or with the aid of large disparity gradients, the diplopia thresholds reduce.[11] On the other hand, when the changes in singleness due to disparity are less conspicuous, for example, as a result of the absence of conspicuous monocular displacements or the occurrence of stereoscopic relative depth, the diplopia thresholds are higher.

The magnitude of the diplopia threshold was finally found to depend on the amount of training received by the subject and on systematic differences between subjects, in particular the optimum optical correction applied.

Table 5
Singleness Limits (SL) and Doubleness Thresholds (DT) With Their Standard Deviations (in Minutes of Arc) for Horizontal Disparity in the Fovea, 4.5° to the Right of the Fixation Point (4.5/0) and 4.5° Above the Fixation Point (4.5/90)

	Fovea								4.5/0								4.5/90							
	160 Msec				.4 Arc Min/Sec				160 Msec				1.6 Arc Min/Sec				160 Msec				1.6 Arc Min/Sec			
	SL		DT		SL		DT		SL		DT		SL		DT		SL		DT		SL		DT	
Subject	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
A.L.D.	4.8	1.5	7.5	1.5	3.9	.7	7.7	.7	13.5	7.4	23.1	11.3	19.3	4.2	50.2	5.9	13.6	12.5	32.9	18.7	14.8	4.1	52.1	4.9
C.J.D.	14.3	4.7	22.2	3.6	6.0	1.9	15.1	1.9	58	25	135	28	18.4	7.3	32.2	5.8	38	15	53	15	20.1	5.5	43.5	6.6

Our results show that there is *no* need to assume interference due to initial appearance of binocular disparity for tachistoscopically presented test stimuli on the magnitude of the diplopia threshold. This may be concluded from the fact that the diplopia thresholds obtained with a continuously presented test stimulus were not consistently higher than those obtained for a tachistoscopically presented test stimulus.

What is the Diplopia Threshold?

Our results strongly suggest that the diplopia threshold is, in essence, not the rigid boundary of a dead zone, but a disparity level corresponding to a lenient criterion for singleness which leads to a useful interpretation of the percept of the stimulus without disparity, given the variability of this percept, due to intrinsic noise in the disparity domain.

What is Binocular Fusion?

The occurrence of binocular single vision in spite of disparities is generally ascribed to a process called binocular fusion. Our data confirm the conclusion of Kaufman and Arditi (1976a, 1976b) that the word "fusion" should not be interpreted too literally. It should be seen as the combined occurrence of an *accurate combination* of monocular *localizations* resulting in either stereoscopic depth or an intermediate binocular localization (Sheedy & Fry, 1979) and an *inaccurate and inconspicuous* representation of the part of the disparity information that encodes the appearance of the image, already accurately determined before binocular combination.

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NOTES

1. In this paper, all retinal disparities and dimensions of perceived images are expressed in degrees of arc or minutes of arc, which, for the sake of simplicity, are denoted by, for example, "5°" or "1′," respectively.

2. With the exception of the "induced effect": In some subjects and under some stimulus conditions, stereoscopic depth can be induced by vertical magnification of one of a pair of monocular images (Ogle, 1964).

3. The line width was measured at a fixation distance of 10 cm by determining the separation between two lines giving rise to a just noticeable gap.

4. Analysis of variance shows that the *difference between* the geometric means of the *singleness limits* and the *doubleness thresholds* is significant $[F(1,4) > 23, p < .01]$ for all stimulus conditions. The effect of the criterion on the geometric means of the signal-to-noise ratios is significant ($p < .05$) only for "0, 200 msec" $[F(1,4) = 28, p < .01]$, for "−, 200 msec" $[F(1,4) = 16.5, p < .02]$, and for "−, .4 arc min/sec" $[F(1,4) = 21.7, p < .01]$.

The *singleness limits* for the test line in combination with the fixation line are significantly lower than those for the test line in combination with the fixation circles $[F(1,4) > 20, p < .01]$. The singleness limits expressed in standard-deviation units are lower for the test line in combination with the fixation line when the former is presented tachistoscopically $[F(1,4) > 7.4, p < .05]$.

The *doubleness thresholds* for the tachistoscopically presented test line in combination with the fixation line are lower than those of the tachistoscopically presented test line in combination with the fixation circles $[F(1,4) > 15, p < .02]$. The fixation marker does not have a significant effect on the doubleness thresholds expressed in standard-deviation units $[F(1,4) < 5.5, p > .06]$.

The only significant effect of the *presentation time* on the size of the disparity thresholds occurs for the singleness limits in combination with the fixation circle $[F(1,4) = 25, p < .01]$. The presentation time influences the magnitude of the singleness limits expressed in standard-deviation units for both fixation stimuli $[F(1,4) > 12, p < .02]$ and the magnitude of the doubleness thresholds expressed in standard-deviation units when the fixation line is used $[F(1,4) = 14, p < .02]$.

5. Analysis of variance of the effect of the criterion and stimulus conditions on geometric means shows that differences between subjects are not a significant source of variance $[F(1,4) < 7.7, p > .05]$ for the thresholds expressed in standard-deviation units, whereas these differences were significant $[F(1,4) > 11, p < .02]$ for the absolute values of the thresholds.

6. This agrees with results obtained by Palmer (1961). He found that the frequency of seeing a single image does not always reach the value 1.0 for a stimulus without disparity in the visual periphery, which implies that even this stimulus must have been seen as double in part of the presentations.

7. These cyclophorias were discovered only after the investigation had been under way for some time. Their value was estimated

with the aid of a pair of dichoptic horizontal lines, seen in diplopia.

8. See Appendix.

9. It is our finding that relative depth is not always seen under all stimulus conditions. If it is not seen, the percept at intermediate horizontal disparities is remarkably similar to that at intermediate vertical disparities.

10. When Subject A.L.D. looked at the upper part of a vertical fixation line that was 30′ long and positioned 3′ below a 30′-long vertical test line with horizontal disparity, the doubleness threshold even fell to 2.2′ ± .8′ when the test line was presented tachistoscopically with a presentation time of 200 msec.

11. An important example of a dichoptic stimulus with highly noticeable monocular displacement is a stimulus with cyclodisparity, since the thresholds for the perception of tilt in monocular lines with cyclorotation are low compared with the corresponding diplopia thresholds (see, e.g, Kaufman & Arditi, 1976b).

APPENDIX

Threshold Considerations

Different assumptions may be made concerning the processes underlying the diplopia threshold. The consequences of the various assumptions will be discussed.

1. If the disparity thresholds are "real" thresholds, that is, if they correspond to the boundary of a dead zone, which is wide in comparison with the intrinsic noise in the disparity domain, then the following relation exists between the detection threshold (obtained in a discrimination task), the singleness limit, and the doubleness threshold (both obtained in a three-alternative classification task):

Detection threshold = singleness limit

= doubleness threshold.

This can be understood when it is remembered that all three thresholds here refer to the disparity that gives 50% frequency of seeing the disparity in the stimulus.

2. If, on the other hand, the disparity thresholds are not "real" thresholds but are determined with reference to criteria chosen from a continuous scale of possible criteria extending to zero disparity in a disparity domain with constant additive intrinsic noise, then the detection threshold will be determined by signal-detection considerations.

If no loss of disparity information may be expected during signal detection, the following is obtained:

Detection threshold = .955 × standard deviation of singleness limit

= .955 × standard deviation of doubleness threshold.

Signal detection with loss of information about the sign of the disparity would result in:

Detection threshold = 1.49 × standard deviation of singleness limit

= 1.49 × standard deviation of doubleness threshold.

These relations may be derived as follows: In the two-alternative forced-choice procedure, the subject is comparing the percepts of two stimuli presented in succession in order to determine which percept embodies a disparity. In the three-alternative classification, the subject is assessing the percept of each stimulus presented with reference to two criteria, that is, two disparity levels.

(a) Assume that the internal representation of the disparity in the test stimulus is increased with a sample of a normalized Gaussian distribution so that the density function of a large number of internal representations of the same stimulus disparity is:

$$p(d) = \frac{1}{\sigma_d\sqrt{2\pi}} \exp\left[\frac{-(d-\delta)^2}{2\sigma_d^2}\right],$$

where d = disparity, δ = disparity in the test stimulus, and σ_d = standard deviation of the additive Gaussian noise.

(b) Assume that the internal representations of stimuli presented in succession are mutually independent.

Under these assumptions, the statistics of the decisions in the three-alternative classification procedure are governed by the distribution p(d). This implies that the standard deviation of the disparity thresholds obtained with this procedure is equal to σ_d.

The frequency of correct discrimination, $P_c(\delta)$, in the two-alternative forced-choice situation when there is no loss of disparity information, is given by:

$$P_c(\delta) = \int_{-\infty}^{+\infty} p_{sn}(d=x) P_n(d<x)\,\partial x,$$

where p_{sn} = the probability that the internal representation of the stimulus *with* disparity is located at disparity x,

$$p_{sn} = \frac{1}{\sigma_d\sqrt{2\pi}} \exp\left[\frac{-(x-\delta)^2}{2\sigma_d^2}\right]$$

and $P_n(d < x)$ = the probability that the internal representation of the stimulus *without* disparity is located at a disparity that is smaller than x,

$$P_n(d<x) = \int_{-\infty}^{x} \frac{1}{\sigma_d\sqrt{2\pi}} \exp\left[\frac{-d^2}{2\sigma_d^2}\right] \partial d.$$

The frequency of correct detection will be 50% for $P_c(\delta') = .75$, which corresponds to $\delta' = .955\sigma_d$.

The frequency of correct discrimination, $P_c'(\delta)$, in the two-alternative forced-choice procedure when information about the sign of the disparity is lost is given by:

$$P_c'(\delta) = \int_0^{\infty} \{[p_{sn}(d=+x) + p_{sn}(d=-x)] P_n(-x<d<+x)\}\,\partial x,$$

where $p_{sn}(d = \pm x)$ = the probability that the internal representation of the stimulus *with* disparity is located at disparity ±x.

$$p_{sn}(d = \pm x) = \frac{1}{\sigma_d\sqrt{2\pi}} \exp\left[\frac{-(\pm x - \delta)^2}{2\sigma_d^2}\right]$$

and $P_n(-x < d < +x)$ = the probability that the internal representation of the stimulus without disparity is located between the disparities $-x$ and $+x$,

$$P_n(-x < d < +x) = \int_{-x}^{+x} \frac{1}{\sigma_d\sqrt{2\pi}} \exp\left[\frac{-d^2}{2\sigma_d^2}\right] \partial d.$$

The frequency of correct detection will be 50% for $P_c'(\delta'') = .75$, which corresponds to $\delta'' = 1.49\sigma_d$.

(Received for publication June, 30, 1980;
accepted revision received January 12, 1981.)

2.2 THE EFFECT OF PRESENTATION TIME ON DETECTION AND DIPLOPIA THRESHOLDS FOR VERTICAL DISPARITIES

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ABSTRACT

Detection and diplopia thresholds for vertical disparities are found to decrease when the presentation time of the stimulus with disparity is increased between 20 msec and 2 sec. This result supports the following notions previously put forward in literature: a) the human visual system embodies detection processes which reveal vertical disparities; there is no sensory fusion mechanism in this system that gradually conceals vertical disparities; b) the detection of vertical disparity in tachistoscopically presented stimuli is not based upon the initial appearance of the stimulus with disparity.

INTRODUCTION

There is disagreement in the literature about the nature of the processes underlying singleness of binocular vision in spite of retinal disparities. Some investigators ascribe its occurrence to an active fusion mechanism that eliminates disparities (Kertesz and Sullivan, 1976). Others claim that it simply reflects a failure to detect the disruption of singleness caused by disparities. The latter hypothesis is based on the findings that singleness of binocular vision is just due to use of a lenient criterion amidst the many possible criteria which could be used to judge the disparity information - and that this particular type of disparity information is inaccurately and inconspicuously coded by the relevant parts of the human visual system (Kaufman and Arditi, 1976a,

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1976b; Arditi and Kaufman, 1978; Duwaer and Van den Brink, 1981a).

An important stimulus parameter which has not yet been dealt with in this discussion is the effect of the presentation time of the stimulus with disparity.

This presentation time can be used as a tool to discriminate between the two above-mentioned hypotheses. If an elimination mechanism such as fusion is involved, the dynamics of the perceptual system should give better elimination the longer the disparity is presented. Hence, the various thresholds for the detection or recognition of disparities should rise with increasing presentation time[1]. On the other hand, if binocular singleness is simply due to a detection failure, the detection and recognition of disparities should improve the longer the disparity is present. This would imply that the disparity thresholds should fall with increasing presentation time.

Experiments with a variable presentation time may also help to resolve the disagreement between Kertesz and Sullivan (1976) on the one hand and Kaufman and Arditi (1976a, 1976b) and Arditi and Kaufman (1978) on the other, about the influence of the initial appearance of a binocular disparity in tachistoscopic presentation on the detectability of the disparity. If the presentation time is short, only the initial appearance will be perceived. If the detectability of the disparity at short presentation times - which must be based on the initial appearance - is lower than that at long presentation times, the latter must be based not upon the initial appearance, but upon final appearances.

So far, the effect of presentation time has only been determined for horizontal disparities in three studies (Palmer, 1961; Mitchell, 1966; Woo, 1974) which produced inconsistent results, and for detection thresholds for relative horizontal disparities when depth cues were found to determine the detection (Ogle and Weil, 1958; Shortess and Krauskopf, 1961).

The discussion about the mechanism underlying binocular single vision was, however, based upon data collected with vertical disparities, where stereoscopic depth effects that interfere with interpretation of the percepts and the results can be avoided.

The purposes of the present study were:

-to provide data on the effect of presentation time on the detection and diplopia thresholds for vertical disparities;

-to use these data to throw light on the mechanism underlying binocular single vision and the role of the initial appearance of binocular disparity.

METHODS

The effect of presentation time on the detection and diplopia thresholds was studied in a highly practised subject (ALD, one of the authors [2]) for the stimulus with aniseikonic vertical disparity shown in Fig. 1. This stimulus was chosen because it did not provide the subject with depth cues and because it does not cause vergence eye-movements in response to the disparity between the lines (Duwaer and Van den Brink, 1981c). Thanks to the absence of vergence eye-movements, presentation times longer than 0.2 sec (the reaction time of vergence eye-movements; Westheimer and Mitchell, 1956) can be used.

This line stimulus was presented in an electronic stereoscope consisting of two (HP 1321A) XYZ displays (white P31 phosphor) mounted 105 cm from the subject's eyes with a white background (mean luminance level 3 cd/m^2, sides 15°) [3]. The line width of the stimuli amounted to 0.35 mm or 1.2'. The luminance of the stimuli was adjusted to 1.8 log units above the (contrast) perception threshold at long observation times, unless mention is specifically made to the contrary. The subject's head was immobilized with a bite-board.

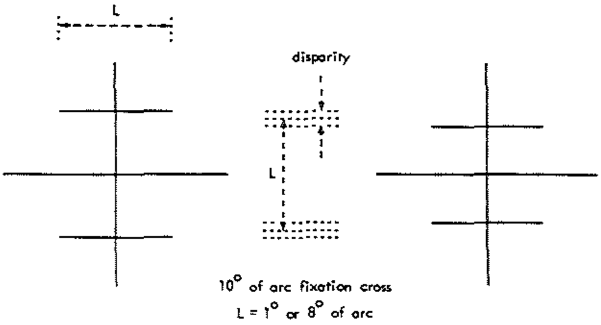


Fig. 1. Schematic representation of the stimuli presented to the left and right eyes. A disparity of opposite sign is obtained when the displacements of the lines are such that the separation between the upper and lower line is larger (instead of smaller) in the right eye than in the left eye.

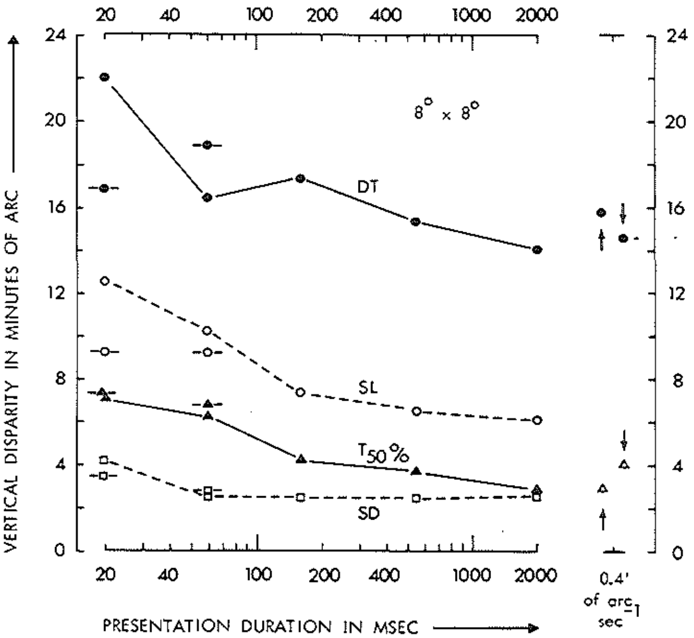
The stimulus (see Fig. 1) consisted of a continuously visible cross fixated at the centre, together with a pair of horizontal lines presented either tachistoscopically with a constant disparity and presentation times of 20, 60, 160, 560 or 2000 msec, or continuously while the disparity slowly increased or decreased at rates of 0.2'/sec or 0.4'/sec.

The diplopia thresholds for tachistoscopic presentation were determined by getting the subject to classify the percept of the upper and lower horizontal lines as unequivocally single (i.e. the percepts of one line without disparity), unequivocally double (i.e. two separate lines), or neither unequivocally single nor unequivocally double. In the latter case, the lines seemed to exhibit an irritating fluctuation in some property or properties which are difficult to define; we shall denote this characteristic by 'restlessness' here. In addition, the line percept resembled that found in binocular rivalry, and tended to be blurred and broadened. The frequency of seeing (FOS) these various alternatives was determined as a function of disparity. The experiments were carried out in sessions during which the disparity was selected at random by a microprocessor from 24 preselected values, so as to evoke all possible percepts.

Each disparity value was presented 20 times. The 3 FOS curves obtained were fitted by convolution of normalized Gaussian noise with hypothetical disparity ranges, where either unequivocal doubleness, or unequivocal singleness, or neither is always seen (see Duwaer and Van den Brink, 1981a). The disparity at which (after deconvolution) unequivocal singleness ends will be called the singleness limit (SL), and the disparity at which unequivocal doubleness starts the doubleness threshold (DT). These two values provide a lower and upper limit for the diplopia threshold. The mean values of SL and DT at positive and negative disparities (see the legend to Fig. 1) and the mean standard deviation (SD) of the fitted Gaussian noise are presented in Fig. 2 for test stimuli measuring $1^{\circ} \times 1^{\circ}$ and $8^{\circ} \times 8^{\circ}$. The lines connect experimental points obtained at the same luminance (1.8 log units above the perception threshold with a presentation time of 2 sec). The points for presentation times of 20 msec and 60 msec which are marked by small horizontal lines on either side of the symbols, were obtained when the luminance was adjusted to 1.8 log units above the perception threshold at those particular presentation times. It will be seen that they are higher than the perception thresholds with the longer presentation time of 2 sec.

Furthermore, detection thresholds for tachistoscopic presentation were determined by getting the subject to discriminate between test lines with and without disparity. This task was performed in a temporal 2-interval forced-choice procedure (interstimulus interval 3 seconds). The positive and negative disparities giving 50% detection 4) were each determined by linear interpolation from at least 4 detection frequencies between 0.00 and 1.00 that were each determined from 50 trials. The mean result is denoted by $T_{50\%}$.

Disparity thresholds were also determined in 20 runs where the size of the disparity in a continuously visible test stimulus slowly increased from zero to a preset value, and in 20 runs where the disparity slowly decreased from a preset value to zero. This presentation mode has the obvious advantage of avoiding possible transient effects that might interfere with tachistoscopic presentation 5). The subject was asked to press a button whenever the perceived stimulus was neither 'ideally single' nor 'unequivocally double'. The transitional percepts observed varied from an unequivocally single line with a faint 'glow' to a restless, blurred, broadened line with increasing disparity. The disparity at which 'ideally single' vision ends gives the detection threshold (open triangles in Fig. 2) while the disparity where unequivocal doubleness starts gives the doubleness threshold (DT).



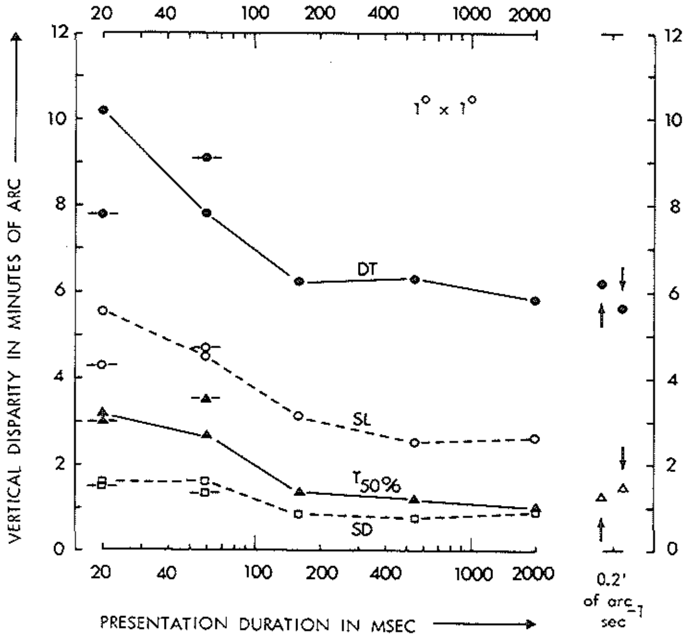


Fig. 2. Doubleness thresholds (DT: solid circles), singleness limits (SL: open circles), detection thresholds ($T_{50\%}$: solid triangles; for continuously visible test lines: open triangles) and mean standard deviation of DT and SL (SD: open squares), as functions of the presentation time. The lines connect experimental points obtained at the same luminance (1.8 log units above the perception threshold at a presentation time of 2 sec). The data obtained after correction for the decrease of brightness found at presentation times of 20 msec and 60 msec are indicated by symbols with small horizontal lines on either side. The data obtained with slowly changing disparities in continuously visible test lines are plotted on the right-hand side of each graph. The standard errors of SL and DT are a factor 5 smaller than the specified standard deviation (SD). The standard errors of the detection thresholds are a factor 10 smaller than the thresholds. Fig. 2 shows data obtained with a $8^{\circ} \times 8^{\circ}$ test stimulus ($L=8^{\circ}$, see Fig. 1) and data for a $1^{\circ} \times 1^{\circ}$ test stimulus ($L=1^{\circ}$).

RESULTS

The major findings are:

-the two diplopia thresholds (DT and SL), their mean standard deviation (SD) and the detection thresholds ($T_{50\%}$) fall with increasing presentation time especially up to about 0.2 sec. This effect can only partially be ascribed to changing brightness due to the finite integration time of luminance processing, because the drop also occurs when the luminance of the test lines is increased at the short presentation times in order to correct for this brightness effect (data obtained with this correction are denoted by symbols with small horizontal lines on either side).

-the thresholds for tachistoscopic presentation with long presentation times hardly differ from those obtained with continuously visible test lines where the disparity slowly increases or decreases[6)]. This demonstrates that there are no interfering transients in tachistoscopic presentation.

A third finding can be deduced from a detailed comparison of the detection threshold ($T_{50\%}$) and the standard deviation (SD).

It has been shown in previous studies (Duwaer and Van den Brink, 1981a, 1981c), that the quotient ($T_{50\%}$/SD) can be used to evaluate whether the detection threshold ($T_{50\%}$) obtained in a 2-alternative forced-choice procedure can be accounted for by pure signal detection without loss of disparity informa-

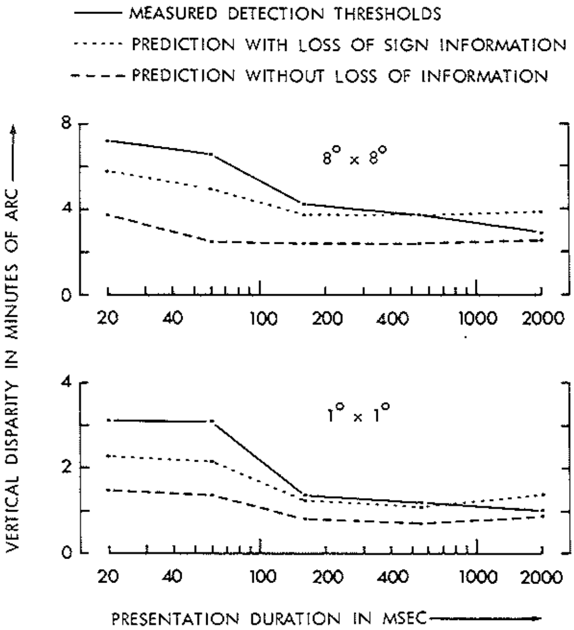


Fig. 3. Comparison of the measured detection thresholds and the predicted values when there is loss of information about the sign of disparities ($T_{50\%, \text{ predicted}} = 1.49$ SD) and when there is no loss of disparity information ($T_{50\%, \text{ predicted}} = 0.955$ SD). Measured points at 20 msec and 60 msec presentation times represent the means of the data for the two luminance levels.

tion. In the case of signal detection without loss of disparity information - which implies that detection failures are only ascribed to the occurrence of noise (see also Fig. 4) - the detection threshold ($T_{50\%}$) should be equal to 0.955 times the standard deviation (SD). Comparison of this prediction with the measured detection thresholds (see Fig. 3) shows that this hypothesis must be rejected. The measured detection thresholds are systematically larger than the predicted values, which implies there is loss of disparity information.

One evident cause of such loss of disparity information is that disparities of opposite sign (see legend to Fig. 1) result in the same percepts, i.e. blurred, broadened, restless and/or doubled lines. This loss of information about the sign of disparities increases the predicted detection threshold to 1.49 times the standard deviation (see Fig. 4). Comparison of this prediction with the measured detection thresholds (see Fig. 3) suggests that a major part of the loss of disparity information can indeed be accounted for by loss of sign information. We may therefore conclude that a reasonable first-order approximation to the experimental data can be obtained on the assumption of signal detection with loss of sign information and with interference by intrinsic noise of constant level throughout the disparity domain.

Inspection of Fig. 3 shows systematic discrepancies up to 30% between the measured and predicted detection thresholds. The predicted detection thresholds are too low at the shortest presentation times and tend to become too high at the longest presentation times. The discrepancies at the short presentation times can be accounted for by assuming that there is also loss of information about the size of disparity, due to the occurrence of a dead zone.

It can be seen from Fig. 4 that the assumption of a dead zone provides the increase in the predicted detection thresholds that is required at short presentation times. However, the effect of a dead zone on the predicted detection threshold is initially very small. For instance, in order to increase a detection threshold of 1.49 SD-units by 30%, the dead zone must increase from 0 to 1.8 SD-units. This implies that the assessment of whether a comparatively small dead zone does occur, and the estimation of its size if it does, depend strongly on the accuracy of the quotient ($T_{50\%}$/SD) and the validity of the assumptions involved in its calculation. One of these assumptions is that the noise level remains constant throughout the disparity domain. Although previously presented data (Duwaer and Van den Brink, 1981a) and the data collected in this study do support this assumption, statistically non-significant deviations from constancy of noise level were observed. If the noise level does actually vary throughout the disparity domain, this might affect the size of the predicted threshold for two reasons. Firstly, the noise level at the disparity level corresponding to the detection threshold was estimated from the standard deviations of the diplopia thresholds corresponding to higher disparity levels. Secondly, the ratio (disparity level where noise level is estimated)/(disparity level corresponding to the detection threshold) decreases systematically as the presentation time falls. It is thus impossible to exclude the possibility that the discrepancies between the predicted and measured detection thresholds are simply caused by variation of the noise level as a function of the disparity level. This would not be surprising *a priori*, since a change in disparity level would result in the stimulation of other cells that might embody other characteristics.

DISCUSSION

The drop in the detection and diplopia thresholds for vertical disparities with increasing presentation time suggests that it is more likely that there are detection processes which reveal vertical disparities than that there is a fusion mechanism which gradually conceals such disparities. This conclusion supports

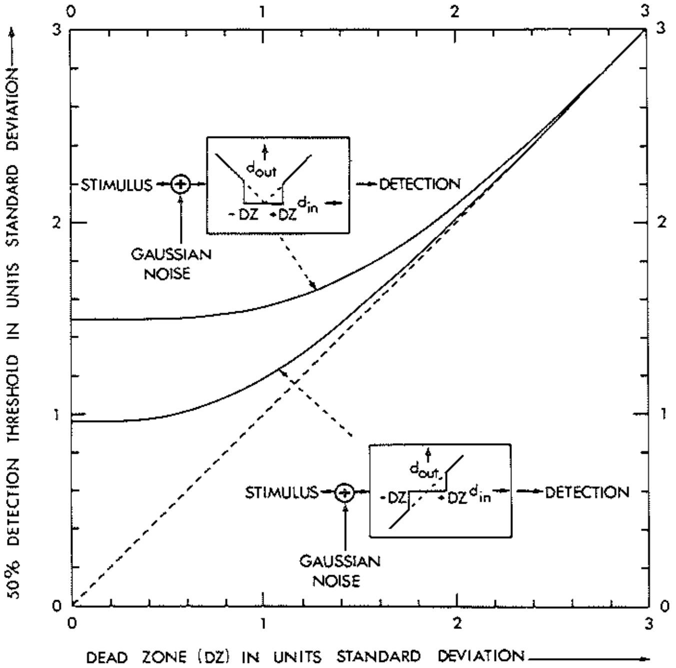


Fig. 4. Theoretical relations between the 50% detection threshold obtained in a two-interval forced-choice procedure and the dead zone, i.e. the range of disparities where information about the size of the disparity is lost. The lower curve represents the relation when there is only loss of size information. The upper curve represents the relation when there is also loss of sign information.

These curves were calculated using the disparity transformations shown in the inset diagrams. A disparity transformation is initiated by a presentation of the stimulus with or without disparity. The disparity of the stimulus is then changed by addition of a sample of Gaussian noise with the following distribution function for a large number of successive samples:

$$p(d) = \frac{1}{\sigma_d \sqrt{2\pi}} \exp\{\frac{-d^2}{2\sigma_d{}^2}\}$$

where d=disparity and σ_d=standard deviation of the additive Gaussian noise.

In the lower inset diagram, the resulting disparity passes through a dead zone in which the effect of input disparities between -DZ and +DZ is eliminated. The output of this dead zone is used by the detector, which compares the transformed disparity of a stimulus with positive or negative disparity with the transformed disparity of a stimulus with zero disparity. The detector determines the largest transformed disparity for stimulus pairs with positive and zero disparities and the smallest transformed disparity for stimulus pairs with negative and zero disparities. This comparison will result in correct identification of the stimulus with non-zero disparity when the transformed disparity of a stimulus with positive (negative) disparity is larger (smaller) than the transformed disparity of a stimulus with zero disparity.

In the upper inset diagram, the disparity becomes zero for values between -DZ and +DZ and also loses its sign before entering the detector. In this case, the detector determines the largest transformed disparity for stimulus pairs with zero and non-zero disparities. This will result in correct identification of the stimulus with non-zero disparity when its transformed disparity is larger than the transformed disparity of the stimulus with zero disparity.

The curves were calculated by determining the stimulus disparity δ that results in a probability of correct identification of 0.75, given the size (DZ) of the dead zone.

Lower curve:
$$0.75=\int_{-\infty}^{DZ} p(-\delta'+d)\{\int_{-\infty}^{d} p(x)\,\partial x\}\partial d+0.5\{\int_{-DZ}^{+DZ} p(-\delta'+d)\,\partial d\}$$
$$\{\int_{-DZ}^{+DZ} p(d)\,\partial d\}+\{\int_{-DZ}^{+DZ} p(-\delta'+d)\,\partial d\}\{\int_{-\infty}^{-DZ} p(d)\,\partial d\}+$$
$$\int_{+DZ}^{\infty} p(-\delta'+d)\{\int_{-\infty}^{d} p(x)\,\partial x\}\partial d$$

Upper curve:
$$0.75=0.5\{\int_{-DZ}^{+DZ} p(-\delta''+d)\,\partial d\}\{\int_{-DZ}^{+DZ} p(d)\,\partial d\}+$$
$$\int_{+DZ}^{\infty}\{p(-\delta''-d)+p(-\delta''+d)\}\{\int_{-d}^{+d} p(x)\,\partial x\}\partial d$$

those of Kaufman and Arditi (1976a, 1976b) and Duwaer and Van den Brink (1981a, 1981c), but is in conflict with the ideas put forward by Kertesz and Sullivan (1976).

A noteworthy implication of this line of reasoning is that the comparatively high detection thresholds for vertical disparity at short presentation times should be interpreted as due to failure of a detection mechanism rather than as the result of a fusion mechanism.

Most vertical disparities in daily life will only be present for a short time, as they are eliminated by vergence eye-movements (see e.g. Duwaer and Van den Brink, 1981b, 1981c). This implies that there is only need for reduced detectability of vertical disparities that are present during the time necessary to complete motoric elimination by vergence eye-movements. The observed reduction in detectability at short presentation times is thus quite a functional arrangement!

It further follows from our study that the detection of vertical disparity in tachistoscopic presentations is based upon final appearances of the stimulus with disparity and not upon its initial appearance. This may be concluded from the finding that the detectability of the disparity in the initial percept is worse than in final percepts, as evidenced by the lower detection thresholds at long presentation times, both with the initial percept (tachistoscopic presentation) and without it (continuous presentation). This conclusion, again, supports those of Kaufman and Arditi (1976b), Arditi and Kaufman (1978), and Duwaer and Van den Brink (1981a, 1981c) and is in conflict with those of Kertesz and Sullivan (1976).

A drop in the detection threshold with increasing presentation time has been observed not only for vertical disparity. A similar result has e.g. also been obtained for relative horizontal disparity when depth cues determine the detection (Ogle and Weil, 1958; Shortess and Krauskopf, 1961). This implies that there is no active fusion mechanism which gradually conceals relative horizontal disparities either. Relative horizontal disparities are thus also more likely to be revealed by detection processes. A revealed relative horizontal disparity may, however, tend to conceal the *doubling* of the binocular image induced by the disparity as such, because a revealed relative horizontal disparity is interpreted as being caused by relative depth that presupposes one *single* binocular image. This suggests that the apparent gradual disappearance of diplopia induced by horizontal disparity as such which may be observed in complex scenes should be ascribed to detection processes that need time to reveal relative horizontal disparities 7).

The effect of presentation time on the detection threshold for relative horizontal disparity and relative displacement in a vernier paradigm cannot be attributed to detection processes that use the extra information in the spatial domain coming from retinal image displacements due to involuntary eye-movements during presentation of the stimulus (Shortess and Krauskopf, 1961; Keesey, 1960). Variation in the retinal image displacement due to involuntary eye movements is thus unlikely to be the cause of the effect of presentation time on the detection thresholds for vertical disparity.

The overall result of the extra information provided by longer observation times is likely to be an increase of the signal-to-noise ratio of the internal representation of the spatial parameter. At the present state of our knowledge of the neural mechanisms involved, we can only speculate about the way in which this is accomplished.

ACKNOWLEDGEMENTS

This research was supported by a grant from the Netherlands Organization for the Advancement of Pure Research (Z.W.O.). We would also like to thank Mrs. A. E.H. Peters and Dr. C.M.M. de Weert for helpful discussions and Mr. C.J. Keemink and Mr. J.B.P. van Deursen for their technical assistance.

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NOTES

1. A necessary condition for a rise in the thresholds with increasing presentation durations is that the detection or recognition should be based upon the final appearances of the image with disparity and not upon transient initial appearances.

2. A serious drawback of the use of dichoptic stimuli with vertical disparities is that the subject has to be highly practised in order to be reasonably sure of stable sensory performance, since the thresholds fall with increasing practice, even when the test subject has already had a substantial amount of practice (Duwaer and Van den Brink, 1981a; Arditi and Kaufman, 1978).

Subject ALD has normal acuity, stereopsis and binocular single vision.

3. In this paper, all angular measures will be expressed simply in degrees ($^{\circ}$) or minutes (') without the qualification 'of arc' each time.

4. The percentage detection is calculated from the percentage identification by correction for the a-priori detection probability according to the expression:

% detection = 2 x (% identification - 50).

5. Transient appearances in the disparity domain are more reliably avoided by slowly increasing and decreasing the disparity in continuously visible stimuli than by gradual appearance and disappearance of the stimuli with disparity, by luminance variation. The latter method was used by Arditi and Kaufman (1978) in their study of the possible interference of the initial appearance of binocular disparity on the detection of tachistoscopically presented disparities.

6. During the determination of detection thresholds with continuously visible test lines in which the disparity slowly increased, the subject was asked to indicate at which disparity the percept started to deviate from the percept of the stimulus without disparity which he had just seen. This is comparable to the conditions under which detection thresholds for tachistoscopically presented test stimuli were determined. On the other hand, if the disparity falls during the experimental run, the reference percept of the stimulus without disparity is only available in the form of a memorized internal representation. This implies that the detection thresholds for tachistoscopic presentation should be compared with those for continuously visible lines in which the disparity is slowly increased.

It should be noted that such a restriction is not necessary for the doubleness thresholds, because these thresholds are determined by classification using an internal representation of doubleness, irrespective of the mode of presentation.

7. The major cause of the disappearance of diplopia induced by horizontal disparities around the fixation point is elimination of these disparities by vergence eye-movements.

2.3 DETECTION OF VERTICAL DISPARITIES

A.L. Duwaer and G. van den Brink*

ABSTRACT

Psychometric curves determined for the detection of differences between vertical disparities as a function of the reference disparity for three presentation times (20 msec, 160 msec and 2 sec) and for two eccentricities of the stimulus (0.5° and 4°) are presented.

The results show that the detectability of disparity differences first increases and then decreases when the reference disparity is increased from zero. It further appears that the only effect of the stimulus presentation time and eccentricity on the psychometric curves and their dependency on the reference disparity is that the effective disparities observed are multiplied by a constant factor.

The experimental data can be described by a signal detection model with two special features around zero disparity where binocular single vision occurs, viz. loss of information about the sign of disparity and presence of intrinsic noise at a level up to 25% higher than the minimum level found at intermediate disparities.

INTRODUCTION

The phenomenon of binocular single vision despite retinal disparities has long been ascribed to the existence of a sensory dead zone for disparities (known as Panum's area) in which information about the size of disparity is eliminated by a fusional mechanism. Recent researches have, however, provided strong indications against this traditional view; they suggest that singleness of binocular vision is simply the result of use of a lenient criterion chosen from

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among many possible criteria for judging the rather inaccurate, not very reproducible information about singleness of doubleness provided by retinal disparity. Observers tend to use a lenient criterion for singleness because the changes in the singleness of the binocular percepts introduced by the disparity are processed by the visual apparatus in such a way that the overall visual impression received by the subject is relatively inconspicuous and vague: a separation equal to the disparity can be observed much more clearly when the same monocular stimuli are presented to a single eye.

The idea that singleness of binocular vision is brought about by the use of lenient criteria and *not* by sensory dead zones for disparities is based on the observation that observers can judge disparity information about singleness or doubleness consistently and about as accurately using sharper criteria at lower disparities (Duwaer and Van den Brink, 1981a), and - even in the absence of stereoscopic depth cues - can reliably detect disparities much smaller than the 'diplopia threshold' i.e. the disparity at which binocular single vision ends and diplopia emerges (Kaufman and Arditi, 1976a, 1976b; Duwaer and Van den Brink, 1981a, 1981b, 1981c). It should however be borne in mind that observers do have to be specially instructed or biased to use these sharper singleness criteria at lower disparities, e.g. by getting them to discriminate between zero and nonzero disparities.

The idea that there may be no sensory fusion mechanism eliminating retinal disparities, as postulated in traditional theories, is based not only on the apparent absence of sensory dead zones for disparities but also on the results of an analysis of the effect of the presentation time of a disparity on its detection and recognition on the basis of deteriorated singleness. If a fusion mechanism were involved, the detection and recognition of the disparity should get worse at longer presentation times because the dynamics of this mechanism would be expected to give better elimination the longer the disparity is presented. The detection and recognition was, however, found to improve with increasing presentation time. This suggests that it is much more likely that detection and recognition of retinal disparity is hampered by some kind of failure of a 'signal-detection' process (disparity being the signal) aimed at revealing the disparity of which the performance improves the longer the disparity is presented (Duwaer and Van den Brink, 1981c)[1).

These recent researches thus suggest that the fusional mechanism postulated in traditional theories should be replaced by some kind of signal-detection process of limited detection performance. This limited performance seems to be primarily due to the tendency of observers to use lenient assessment criteria, to the presence of a certain amount of intrinsic noise throughout the disparity domain (reflecting the limited accuracy and reproducibility with which disparity information is coded), and to loss of information about the *sign* of the disparity (reflecting the fact that disparities of opposite sign produce the same separations between the monocular images; see e.g. Fig. 1; Duwaer and Van den Brink, 1981a, 1981c). It should be noted that these results suggest that the only phenomenon encountered around zero disparity (where binocular singleness occurs) which is not found at higher disparities (where diplopia occurs) is the (in itself trivial) loss of sign information.

We designed an experiment which can throw new light on this issue of the kind of binocular process operating around zero disparity, by determining the detectability of disparity differences - i.e. the acuity with which a stimulus of given disparity can be discriminated from a stimulus with reference disparity - as a function of the reference disparity. Zero reference disparity (turning the experiments into common ones on the detectability of disparities) is then considered to be just one of the many possible values. The underlying idea is as follows: Discrimination between low disparities and zero disparity is an instance of the more general task of discriminating between two disparities of any value. If there is a special kind of binocular process operating around zero disparity, then discrimination between a low disparity and zero disparity (which will be both affected by this process) ought to differ in some way from discrimination between two higher disparities (which will *not* be affected by this process).

As a baseline for the evaluation of the data, the two major predictions concerning the detectability of disparity differences will be derived in the next section using some straightforward signal-detection considerations. The first prediction is that the detectability of disparity differences with zero reference disparity should be worse than the detectability of disparity differences with comparatively large reference disparities, but only by the small factor 1.56 when the detectabilities are characterized as the disparity differences that yield detection rates of 50%. The second major predection arising from the signal-detection considerations is that the detection data obtained under different stimulus conditions should become equal when the disparities are normalized with respect to the noise level, because this noise level is the only free parameter in these considerations. This implies that the only effect of different stimulus conditions on the detection data should be a change in effective disparities by a constant factor. It should be noted that deviations of the data from the baseline set by these two predictions would suggest that there are more special occurrences around zero disparity (where binocular singleness is perceived) than only loss of information about the sign of the disparity.

The detection data were collected in the form of psychometric curves for vertical disparities permitting isolation of the singleness cue from the depth cue that would accompany it for horizontal disparities. The stimuli were presented at two eccentricities (0.5° and 4°)2). Since previous data suggested that a simple signal-detection account of the data might break down at short presentation times (Duwaer and Van den Brink, 1981c), measurements were performed at three presentation times (20 msec, 160 msec and 2 sec) to test this possibility.

METHODS

Subject

The detection data presented were obtained from a subject (ALD, one of the authors), who was highly trained in such sensory tasks. One can therefore be reasonably sure that the data reflect stabilized sensory performance. This subject was a corrected myope (-0.75 D for left and right eyes) and had normal visual acuity, stereopsis and binocular single vision.

Stimulus

The experiments were performed using the stimulus with aniseikonic vertical disparity shown in Fig. 1. This stimulus was chosen a) because it did not provide the subject with depth cues3) and b) because it does not initiate vergence eye-movements in response to the disparity between the lines (Duwaer and Van den Brink, 1981b). Thanks to the absence of vergence eye-movements, presentation times longer than 0.2 sec (the reaction time for vergence eye-movements;

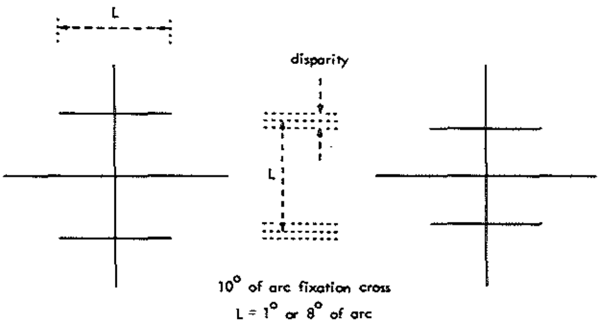

Fig. 1. Schematic representation of the stimuli presented to the left and right eyes. A stimulus with disparity of opposite sign is obtained when the displacements of the lines are such that the separation between the upper and lower line is larger (instead of smaller) in the right eye than in the left eye.

Westheimer and Mitchell, 1956) can be used.

The stimulus consisted of a continuously visible cross at the centre of the visual field and a pair of horizontal test lines (1° x 1° or 8° x 8°) presented tachistoscopically with presentation times of either 2 sec, 160 msec or 20 msec.

This stimulus was presented in an electronic stereoscope consisting of two XYZ displays (HP 1321A with white P31 phosphor) mounted 105 cm from the subjects eyes and a white background (mean luminance 3 cd/m^2, sides 15°). The line width of the stimuli amounted to 0.35 mm, or 1.2'. The luminance of the stimuli was adjusted to 1.8 log units above the (contrast) perception threshold. In order to achieve this brightness level for the presentation time of 20 msec, the luminance had to be increased by about 0.6 log units. We therefore also carried out runs for a presentation time of 20 msec with the same luminance as that of the stimulus at long presentation time. This stimulus condition will be denoted by '20 msec, $L=L_{2000}$' in the figures. The subject's head was immobilized with a bite-board.

Procedure

The subject was asked to discriminate between test lines with a certain test disparity and those with a reference disparity. The only available cue for the detection of a difference between a test disparity and a reference disparity was found to be the amount of deterioration of singleness, which can be characterized as the simultaneous occurrence of restlessness, blurring and broadening of the single line at smaller disparities, gradually changing into separation between two lines at larger disparities4).

The discrimination task was performed in a two-interval forced-choice procedure (interstimulus interval 3 seconds) in which the subject had to decide which interval contained more of the above-mentioned cue, i.e. in which interval the lines were further from pure singleness. The correct interval was randomized with equal a-priori probabilities amounting to 0.5 with the aid of a microprocessor. The subject was highly practised in performing this discrimination task with the sharpest possible criterion as a result of many preliminary discriminations (with and without feedback concerning the correct solutions) in a large number of preceding experiments. The detection frequency for each disparity difference (test disparity - reference disparity) was determined in 100 trials of two successive stimulus presentations each, to give one point on the psychometric curve.

The psychometric curves were plotted with the frequency of seeing more of the above-mentioned cue ('FOS') as ordinate. It may be noted that a FOS of 0.5 corresponds to the chance-level because of the two-interval forced-choice procedure used. A schematic illustration of the FOS curves thus obtained as a function of the test disparity is given in the left-hand graphs of Fig. 2 for zero reference disparity (A), for an intermediate reference disparity (B) and for a comparatively large reference disparity (C). The reference disparities are indicated in this figure by solid bars and 'RE'. The parameter of interest in the present study is not disparity as such, but the difference between the test disparity and the reference disparity. The psychometric curves were, therefore, plotted as a function of the disparity difference as indicated in the right-hand graphs of Fig. 2. The detectability of disparity difference will be defined as the disparity difference that yields detection rates of 50% which corresponds to FOS values of 0.25 or 0.75 for the two-interval forced-choice procedure used. These disparity differences will be called 'Thresholds'. They are indicated by horizontal bars and arrows in Fig. 2.

When the reference disparity is zero (see left-hand graph of Fig. 2A) the FOS increases from the chance level 0.5 to 1.0 for both positive and negative disparity differences. The disparity differences that yield a FOS of 0.75 were taken as thresholds. For positive reference disparities (see left-hand graphs of Figs. 2B and 2C), the FOS also increases for positive disparity differences. The positive disparity differences that yield a FOS of 0.75 were again taken as the thresholds. For negative disparity differences the FOS first decreases below 0.5 before it increases through 0.5 to 1.0. When the FOS did not drop below 0.25 (see left-hand graph of Fig. 2B), the difference between the disparity that yields a FOS of 0.75 and the disparity corresponding to the reference disparity of opposite polarity was taken as the threshold. When the FOS did drop below 0.25 (see left-hand graph of Fig. 2C), the threshold was taken as the negative disparity difference that yields a FOS of 0.25. The thresholds were determined by linear interpolation of detection frequencies that were each obtained from 100 trials of two successive stimulus presentations each.

In fact, in order to eliminate the influence of various systematic changes in the visual performance, these 100 determinations were divided into two lots of 50 trials, the measuring sequence being as follows. For a given set of stimulus conditions, first curve A in the right-hand half of Fig. 2 was determined with 50 trials per point, the various points being taken in a random sequence. Then curve B was determined in the same way, and finally various curves C, the reference disparity being increased each time.

The curves were then determined in the reverse order (various curves C with decreasing reference disparity - B - A), with another 50 trials per experimental point, for the same stimulus conditions, and the results for the two batches of 50 trials were averaged to obtain the final value of each experimental point.

The sets of curves (A, B and C) for other stimulus conditions were then determined in the same way.

The determination of each curve took roughly half a day. If time allowed, two curves could be determined during a single day, the subject being allowed suitable periods of rest between measurements.

The data presented in this study (see Fig. 3) are based on a total of 32900 trials of two successive stimulus presentations each.

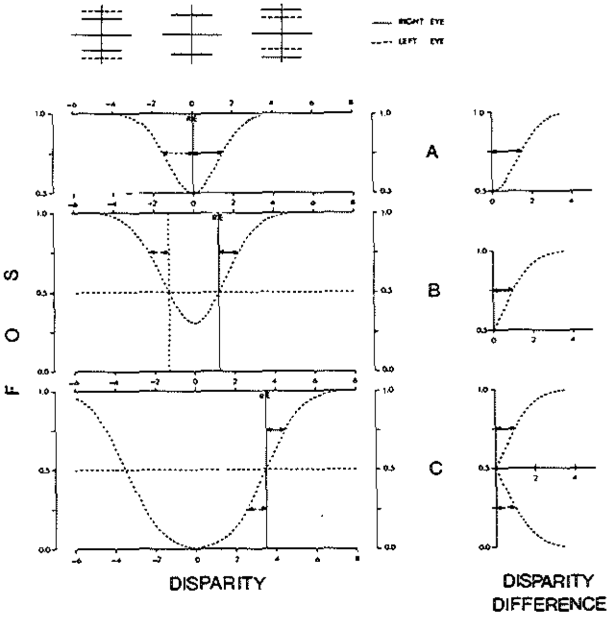

Fig. 2. Schematic representation of the psychometric curves obtained at zero reference disparity (Fig. 2A), an intermediate positive reference disparity (Fig. 2B) and a large positive reference disparity (Fig. 2C). The left-hand curves are plotted as a function of the disparity, the reference disparities being indicated by the vertical bars marked 'RE'. The right-hand curves are plotted as a function of the disparity difference. The horizontal arrows indicate the size of the 'threshold' for the detection of disparity differences. The psychometric curves were calculated using a detection model involving loss of information about the sign of disparities and a constant noise level (measured in terms of the standard deviation of the Gaussian noise). Schematic representations of the stimuli are given above the psychometric curves for negative, zero and positive disparities.

Signal detection considerations

A signal detection model will be used to evaluate the experimental data obtained in this study. This model is generalized in such a way that it can also account for the elimination of disparities e.g. by a fusional mechanism.

The model assumes that the disparity (δ) in the stimulus is first transformed by addition of a disparity value (d) that is a sample of normalized Gaussian noise with the following distribution function for successive samples:

$$p(d)=\frac{1}{\sigma\sqrt{2\pi}}\exp\{\frac{-d^2}{2\sigma^2}\}$$

where σ is the standard deviation of the additive Gaussian noise.

The resulting disparity ($d+\delta$) is then further modified by a transformation function which causes information about the sign of the disparity to be lost and a dead zone (DZ) to occur in which the disparity is eliminated:

$$\begin{array}{ll}\text{output disparity} = |\text{input disparity}| , & |\text{input disparity}| > \text{DZ} \\ \text{output disparity} = \quad 0 , & |\text{input disparity}| \leqslant \text{DZ}\end{array}$$

It should be noted that a nonzero value of DZ turns the model into one in which the elimination of disparities (e.g. by a fusional mechanism) around zero disparity can be accounted for, whereas a zero value for DZ turns the model into one in which loss of sign information can be the only special occurrence around zero disparity.

This transformation is followed by a detection stage which determines whether the thus transformed value of the test disparity δ exceeds the transformed value of the reference disparity δ_{ref}. It can be shown (see e.g. Duwaer and Van den Brink, 1981a, 1981b) that the 'frequency of seeing more signal' (FOS), i.e. the probability that the transformed value of δ is larger than the transformed value of δ_{ref}, is given by

$$\text{FOS}=0.5\{\int_{-DZ}^{+DZ}p(-\delta+d)\,\partial d\}\{\int_{-DZ}^{+DZ}p(-\delta_{ref}+d)\,\partial d\}+\int_{+DZ}^{\infty}\{p(-\delta-d)+p(-\delta+d)\}$$

$$\{\int_{-d}^{+d}p(-\delta_{ref}+x)\,\partial x\}\partial d$$

The same signal transformations can, of course, be used to derive a formula for the frequency of seeing singleness in a classification procedure aimed at determination of the diplopia thresholds. The transformed value of the test disparity δ is then compared with some internal (untransformed) reference disparity δ_{ref} which is set by the particular criterion for singleness used (see e.g. Duwaer and Van den Brink, 1981a).

The simplest case (I) is the model without dead zone (DZ=0) and a constant noise level throughout the disparity domain (σ=SD) which was discussed in the *Introduction*. The predictions derived from this model - indicated by broken lines in Figs. 2, 3, 4 and 5 - will be used as a baseline for the evaluation of the data. One important prediction arising from this line of argument is that the (50% correct) detection threshold occurs at the test disparity δ=1.49 SD units for zero reference disparity (δ_{ref}=0) and at the disparity difference $|\delta-\delta_{ref}|$=0.955 SD units for large reference disparities ($|\delta_{ref}|$>3 SD units), so that the detection threshold for zero reference disparity is a factor 1.56 (=1.49/0.955) larger than that for large reference disparities. In this simplest case, all predictions become equal when the test disparity and reference disparity are both normalized with respect to the value for SD, as SD is the only free parameter. Another major prediction is, therefore, that the detection data obtained under different stimulus conditions that may result in different values for SD, should become equal when the disparities are normalized with respect to the noise level.

Apart from this simplest model, two other theoretical cases will be discussed. Model II had no dead zone (DZ=0), while the noise is a function (f) of the test disparity δ in the stimulus (σ=f(δ)) instead of being constant throughout the disparity domain. This model would imply that the accuracy and reproducibility with which disparity information is coded are different at different disparity values. As such this would not be surprising because of the fact that disparity is a spatial parameter so that a change in disparity will lead to the stimulation of other cells which may embody other characteristics or types of binocular combination. The only feature assumed for model III is that it contains a dead zone (DZ$\neq$0) in which information about the size of disparities is lost. The occurrence of a dead zone might be due to a rigid threshold or to a fusional process gradually eliminating the disparity.

RESULTS AND DISCUSSION

The psychometric curves observed for the 8 different stimulus conditions are presented in Fig. 3. All data obtained with positive disparity differences are denoted by open symbols, and those obtained with negative disparity differences by solid symbols. The corresponding threshold values are given in Table 1.

Fig. 3. Experimentally obtained psychometric curves as a function of the disparity difference (in minutes of arc) for various reference disparities (indicated by different symbols) and eight different stimulus conditions. The broken lines represent the values predicted by the model I described in this paper (involving signal detection with loss of sign information and a standard deviation of the intrinsic noise equal to mean detection threshold for zero reference disparity/1.49). The differences between the calculated psychometric curves at large reference disparities were less than the width of the broken lines. The data obtained at positive disparity differences are indicated by open symbols and those at negative disparity differences by solid symbols.

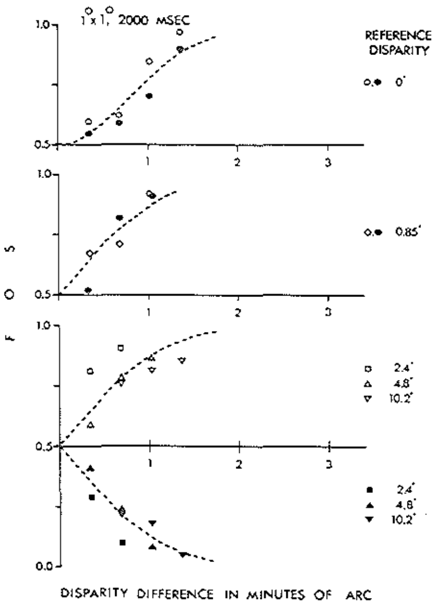

Figure 3A

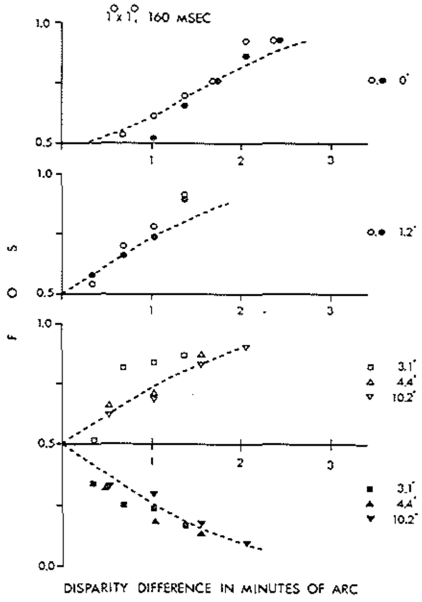

Figure 3B

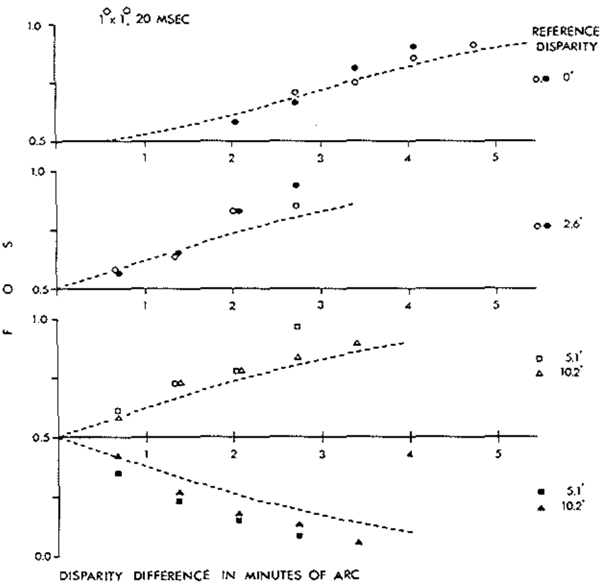

Figure 3C

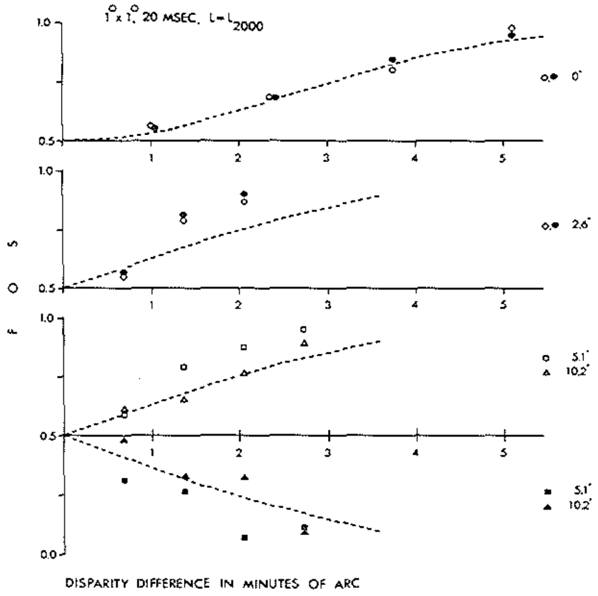

Figure 3D

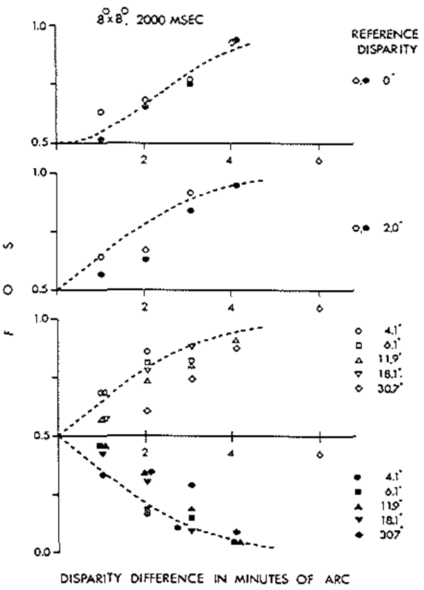

Figure 3E

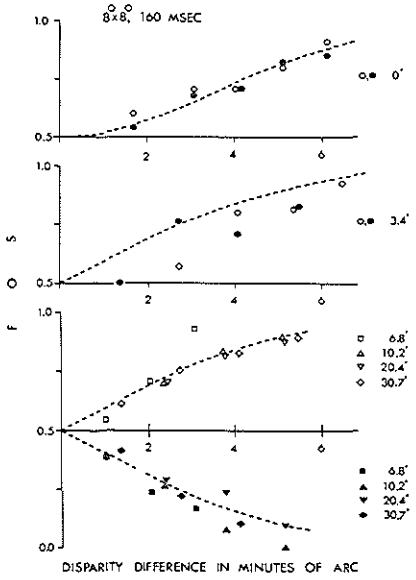

Figure 3F

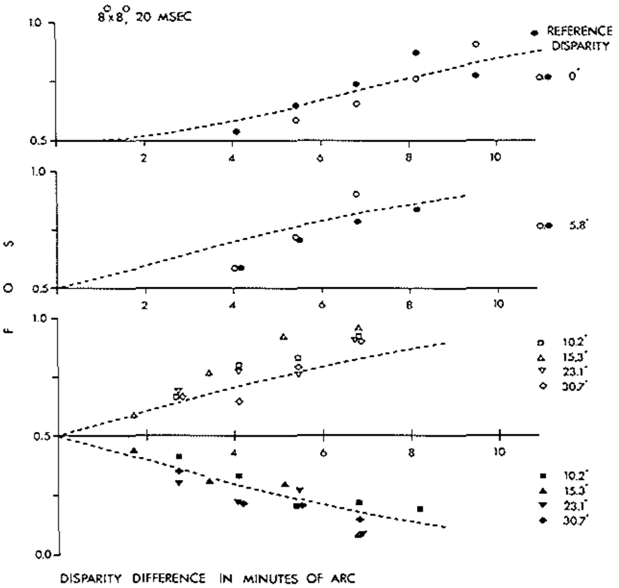

Figure 3G

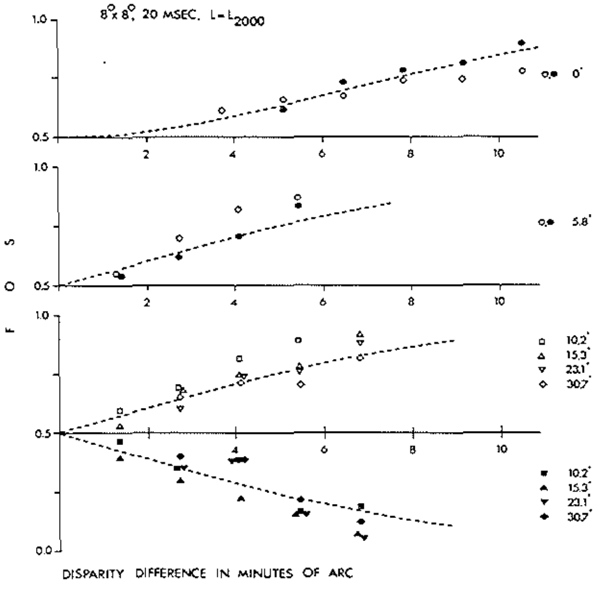

Figure 3H

Table 1. Thresholds (in minutes of arc) for the detection of positive disparity differences (TD^+) and negative disparity differences (TD^-) at different reference disparities (d_{re} in minutes of arc).

Stimulus	d_{re}	TD^-	TD^+	Stimulus	d_{re}	TD^-	TD^+
8° x 8°, 2000 msec	0	-2.8	+2.5	1° x 1°, 2000 msec	0	-1.04	+0.82
	2.0	-2.7	+2.1		0.85	-0.68	+0.64
	4.1	-1.7	+1.4		2.4	-0.41	+0.36
	6.1	-2.2	+2.0		4.8	-0.67	+0.69
	11.9	-2.5	+2.6		10.2	-0.73	+0.84
	18.1	-2.1	+2.1				
	30.7	-2.9	+3.0				
8° x 8°, 160 msec	0	-4.4	+4.0	1° x 1°, 160 msec	0	-1.73	+1.56
	3.4	-4.2	+4.1		1.19	-0.95	+0.88
	6.8	-2.2	+2.1		3.1	-0.91	+0.81
	10.2	-2.7	+3.1		4.4	-0.91	+1.06
	20.4	-3.3	+3.2		10.2	-1.20	+1.23
	30.7	-2.6	+3.3				
8° x 8°, 20 msec	0	-7.7	+7.8	1° x 1°, 20 msec	0	-3.1	+3.5
	5.8	-6.5	+5.6		2.6	-1.67	+1.86
	10.2	-5.9	+3.9		5.1	-1.44	+1.57
	15.3	-4.6	+3.2		10.2	-1.66	+1.94
	23.2	-4.3	+4.3				
	30.7	-4.4	+4.7				
8° x 8°, 20 msec	0	-7.5	+7.7	1° x 1°, 20 msec	0	-3.0	+3.0
$L=L_{2000}$	5.8	-4.4	+3.6	$L=L_{2000}$	2.6	-1.32	+1.39
	10.2	-5.3	+3.4		5.1	-1.44	+1.57
	15.3	-3.8	+4.4		10.2	-1.66	+1.94
	23.2	-4.4	+4.8				
	30.7	-5.1	+5.4				

Inspection of Table 1 and Fig. 3 reveals two major findings:

-Under all stimulus conditions, the detection thresholds first decrease (by about a factor two) and then increase when the reference disparity is increased from zero;

-The corresponding psychometric curves for different presentation times and eccentricities differ primarily in their slopes which suggests that the main effects of presentation time and eccentricity on the psychometric curves may be represented by multiplying the effective disparities by a constant factor.

An important implication of the *second* finding is that a first-order approximation to the psychometric curves can be obtained using a model with one free parameter, viz. a magnification factor in the disparity domain. An example of such a model is the above-mentioned model I, which involves signal detection with loss of sign information (without a dead zone), the standard deviation (SD) of the noise being a parameter which was fixed for each stimulus condition by making the mean detection threshold for zero reference disparity ($T_{50\%}$) equal to 1.49 SD, i.e. the value of the predicted threshold for given SD. The various psychometric curves for the different reference values were then calculated using ($T_{50\%}/1.49$) as standard deviation of the intrinsic noise. The results of these calculations are indicated by broken lines in Fig. 3. It can be seen that they give a reasonable first-order approximation to the experimental data which indicates that the model involving signal detection with loss of sign information and a constant noise level is not far from the truth. It may be noted that the description is as good for the shortest presentation times as it is for the longer ones.

We will now proceed with a more detailed analysis of the data on the basis of Figs. 4 and 5. Fig. 4 displays the thresholds for the detection of disparity difference expressed in SD ($T_{50\%}/1.49$) units as a function of the reference disparity expressed in the same SD units. Fig. 5 displays the psychometric curves obtained with zero reference disparity as a function of the test disparity, also expressed in SD units. The broken lines in these figures again represent the prediction according to model I - i.e. on the assumption of signal detection with loss of sign information and a constant noise level.

It may first of all be noted in Figs. 4 and 5 that the normalized data for the different stimulus conditions are remarkably alike, despite differences in the absolute disparity level (in minutes of arc) of up to a factor 3. This suggests that the main effects of presentation time and eccentricity on the psychometric curves as well as on their dependency on reference disparity may be represented by multiplying the effective disparities by a constant factor.

Inspection of Figs. 4 and 5 also shows that *loss of sign information cannot be the only special thing that happens around zero disparity*. This may be concluded from an unexpected change in the threshold level: the drop in the

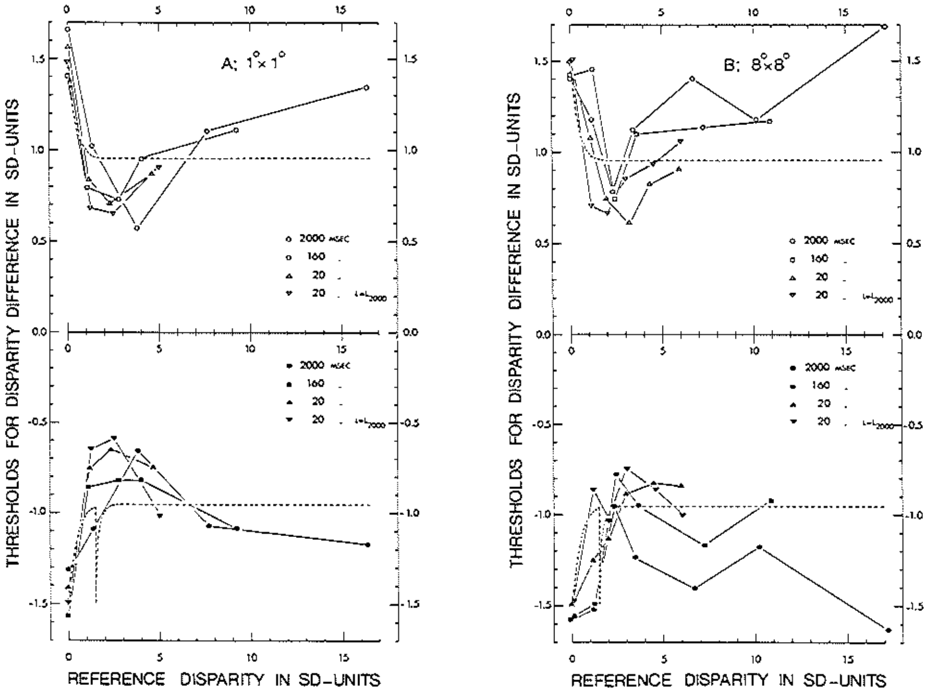

Fig. 4. Thresholds for the detection of disparity differences as a function of the reference disparity, both variables being expressed in standard deviation (=mean detection threshold for zero reference disparity/1.49) units. The data for the 1° x 1° stimulus are plotted in Fig. 4A and those for the 8° x 8° stimulus in Fig. 4B. The different symbols present data determined at different presentation times. The broken line again represents the predicted values on the basis of model I (involving signal detection with loss of sign information). The discontinuity observed at negative disparity differences is simply due to the choice of the thresholds (see Figs. 2B and C). It should be noted that the ordinate scale is a factor 10 greater than that of the absissae.

thresholds when the reference disparity is increased from 0 to 2.5 SD units is larger than expected, while the rise in the threshold at larger reference disparities (see Fig. 4) is not expected at all. This may also be concluded from the underestimation of the FOS values for disparities between 1.5 and 2.5 SD units in the psychometric curves obtained with zero reference disparity (see Fig. 5).

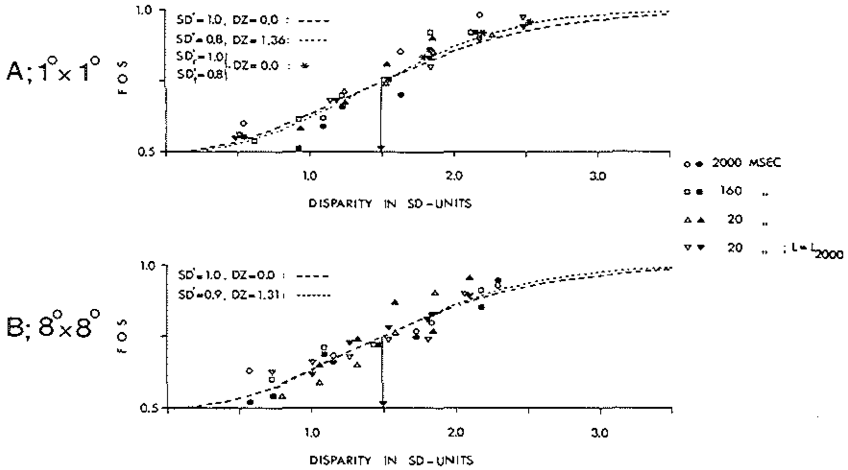

Fig. 5. Psychometric curves for zero reference disparity as a function of the disparity in standard deviation (=mean detection threshold for zero reference disparity/1.49) units. The data of Fig. 5A were obtained with the $1^{\circ} \times 1^{\circ}$ stimulus, and those of Fig. 5B with the $8^{\circ} \times 8^{\circ}$ stimulus. The different symbols represent data for the different presentation times. The various broken and dotted lines and the asteriks represent predictions based on various signal detection models (see text).

The results, therefore, suggest that *there are more special occurrences around zero disparity than only loss of sign information*. Two possible extra occurrences are an increased noise level without dead zone (model II) or a dead zone without increased noise level (model III). These alternatives will be discussed in turn. In *both* alternatives it must be assumed that the noise level increases with increasing disparities above about 2.5 SD units as evidenced by the flattening of the psychometric curves for increasing reference disparities (see Fig. 3) and the increase of the corresponding thresholds (see Fig. 4).

Increased noise level around zero disparity without dead zone (model II)

We would like to start by stressing once again that variation in the noise level throughout the disparity domain (reflecting variation of the accuracy and reproducibility of disparity coding for different disparities) as such is not surprising, since disparity is a spatial parameter. A change in disparity will thus lead to the stimulation of other cells which may embody other characteristics or types of binocular combination.

The unexpected large drop in the threshold when the reference disparity is increased from zero to 2.5 SD units (see Fig. 4) could indicate an increased noise level around zero disparity without dead zone (model II). The assumption of signal detection with loss of sign information but without dead zone would namely require that the standard deviation of the noise for disparities up to at least the detection threshold at 1.49 SD units should amount to 1 SD unit. This standard deviation around zero disparity would then be larger than the actual standard deviation for disparities of 2 SD units, as estimated from the observed thresholds. According to the expression SD = (threshold for detection of disparity difference / 0.955), this standard deviation amounts to 0.8 SD units for the $1^{\circ} \times 1^{\circ}$ stimulus and 0.9 SD units for the $8^{\circ} \times 8^{\circ}$ stimulus. It should be noticed that if the noise level does not increase towards zero disparity, a detection threshold of 1.49 SD units would require the occurrence of a dead zone.

The same increase of noise level from 0.8 SD units (for the $1^{\circ} \times 1^{\circ}$ stimulus) or 0.9 SD units (for the $8^{\circ} \times 8^{\circ}$ stimulus) at disparities of 2 - 2.5 SD units to a level of 1 SD unit at zero disparity without the occurrence of a dead zone can also be used to give a good prediction of the FOS values of the psychometric curves obtained with zero reference disparity (see Fig. 5). Such a description, e.g. with a noise level of 0.8 SD units between 1.8 and 2.5 SD units increasing to 1 SD unit at zero disparity, is indicated in Fig. 5A by asterisks. This description gives an even better fit than the corresponding description with the *same* noise level but with a dead zone (model III) which will be discussed in the next section.

Dead zone without increased noise level around zero disparity (model III)

The unexpectedly large drop in the threshold when the reference disparity is increased from zero to 2.5 SD units (see Fig. 4) and the underestimation of FOS values for disparities between 1.5 and 2.5 SD units in the psychometric curves obtained with zero reference disparity (see Fig. 5) can also be accounted for by the occurrence of a dead zone without increased noise level around zero disparity. For instance, if the standard deviation of the noise remains constant for disparities smaller than 2 SD units, a detection threshold of 1.49 SD units for zero reference disparity can be obtained with a dead zone amounting to 1.36 SD units for a standard deviation of 0.8 SD units and to 1.31 SD units for a standard deviation of 0.9 SD units. The corresponding predictions of the psychometric curves obtained with zero reference disparity are plotted in Fig. 5 as the upper dotted lines. It will be seen that these predictions agree well with the experimental data.

It should be noticed that the magnitude of the dead zone required for these descriptions is closely linked to the noise level (DZ = constant x standard deviation of noise) and would, for instance, fall when the presentation time of the stimulus is increased. This indicates that if there is indeed a dead zone, its occurrence cannot be due to a fusion mechanism of the traditional variety that gradually eliminates information about the size of disparities (see *Introduction*).

CONCLUSIONS

All our experimental data on the detection of vertical disparities can be described to a reasonable approximation by a model involving signal detection without dead zone but with two other special features around zero disparity where binocular single vision occurs, viz. loss of information about the *sign* of the disparity and intrinsic noise at a level up to 25% higher than the minimum level at intermediate disparities (amounting to about 2.5 SD units, i.e. a factor 1.7 above the detection threshold for zero reference disparity). A model with a dead zone and a noise level that is not increased around zero disparity can also be used to describe the data. However, the magnitude of the dead zone required to fit the experimental data would be so small in comparison to the noise level and so closely linked to the latter that we prefer the first-mentioned description without dead zone and with increased noise level around zero disparity, not least because the noise level does not remain constant throughout the disparity domain anyway. If the reader nevertheless prefers a model with dead zone, (s)he should bear in mind that the effect of presentation time on the data obtained indicates that the occurrence of such a dead zone cannot be attributed to a fusion mechanism of the traditional variety gradually reducing the effective *size* of the disparity (to zero).

Our results indicate an increased detectability of disparity differences at intermediate (reference) disparities, even after correction for loss of sign information around zero disparity. Foster (1979) has argued that such an increased detectability of differences between two values of a certain parameter may indicate a boundary between two different internal representations of the parameter. Arguing along these lines, we could thus say that our data seem to point to a boundary between the internal representations of small disparities (leading to binocular single vision) and of large disparities (leading to binocular double vision or diplopia). The boundary between those two internal representations as revealed by the detection data presented here is however not very marked, which explains why it has not been noticed before (see e.g. Kaufman and Arditi, 1976a; Duwaer and Van den Brink, 1981a).

Comparison of the detection threshold with the mean standard deviation of the diplopia thresholds in another study provided indications that a dead zone might develop when the presentation time is shortened (Duwaer and Van den Brink, 1981c). It is now clear that these indications were due to the systematic drop in disparity level in SD ($=T_{50\%}/1.49$) units of the diplopia thresholds and the accompanying drop in noise level in the relevant disparity range of 8 - 2 SD units.

ACKNOWLEDGEMENTS

We would like to thank Dr. C.M.M. de Weert and Mrs. A.E.H. Peters for helpful discussions, Mr. C.J. Keemink and Mr. J.B.P. van Deursen for their technical assistance, Dr. R.H. Bathgate for improving the English, and the Netherlands Organization for the Advancement of Pure Research (Z.W.O.) for the funds which made this investigation possible.

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NOTES

1. It is our finding that in subjects with normal binocular vision without a marked dominance of one of the eyes, a *revealed* retinal disparity - if not eliminated by appropriate vergence eye-movements - usually results in deterioration of singleness that can be characterized as broadening, blurring and 'restlessness' (an irritating fluctuation in some property or properties which are difficult to define) of the image at small disparities, gradually changing into doubling of the image or binocular rivalry (when corresponding retinal locations are stimulated with different stimuli) at larger disparities.

2. In this paper, the retinal disparities and dimensions of perceived images are expressed in degrees of arc and minutes of arc, which for the sake of simplicity are denoted by e.g. 8^o or 2' respectively.

3. Aniseikonic vertical disparity has been claimed to induce stereoscopic depth; this is known in literature as the induced size effect (Ogle, 1938). Stereoscopic depth is however not - at least not in all subjects - induced by aniseikonic vertical disparity when the stimulus contains only horizontal and vertical line segments (Westheimer, 1978; and our own observations). Arditi et al. (1981) have pointed out - in line with a similar suggestion by Westheimer (1978) - that this is to be expected as stereoscopic depth induced by aniseiko-

nic vertical disparity is based on false correlation of noncorresponding horizontally disparate stimulus parts which is likely to occur only for oblique stimulus lines.

4. During the last few sessions with the $8^{\circ} \times 8^{\circ}$ stimulus and a presentation time of 160 msec which were done with the reference disparity of 3.4' and negative disparity differences, the subject saw a disparity-induced change in the orientation in the fronto-parallel plane (so without the occurrence of stereoscopic depth effects) of the *lower* pair of test lines. This change of orientation had not been noticed before and could not be seen under the other stimulus conditions. The subject disregarded this cue during the collection of the remaining detection data for the stimulus in question. The occurrence of this cue was probably due to partial suppression of the left-hand part of the lower test line in one eye and of the right-hand part of this line in the other.

III

COOPERATION BETWEEN MOTOR AND SENSORY PROCESSES UNDERLYING BINOCULAR SINGLE VISION

Chapter III describes the results of two studies of a major aspect associated with binocular single vision which had not been really tackled before, viz. the cooperation between vergence eye-movements aimed at minimizing retinal disparities by aligning the eyes on the one hand and the processes underlying sensory tolerance to these disparities on the other.

In the first study, the magnitude of foveal diplopia thresholds has been compared with the magnitude of 'fixation' disparities occurring spontaneously during continuous binocular fixation due to the limited accuracy of (motor) ocular alignment. Furthermore, the spread of these foveal diplopia thresholds has been compared with the spread of the fixation disparities.

In the second study, the largest vertical (retinal) disparities (at eccentricities of 0.5 to 4 degrees of arc in the visual field) that do not cause image doubling have been compared with the corresponding smallest vertical (retinal) disparities that can initiate vergence eye-movements.

In both studies, a subjective nonius-line method was used to obtain data on ocular alignment (cf. Chapter V).

3.1 FOVEAL DIPLOPIA THRESHOLDS

AND

FIXATION DISPARITIES

A.L. Duwaer and G. van den Brink*

ABSTRACT

Comparison of the magnitude and intrinsic spread of foveal diplopia thresholds with the accuracy of ocular alignment as determined with a subjective alignment method shows that: (a) the accuracy of alignment in the vertical direction (within 1'-2') is remarkably good and much better than in the horizontal direction; (b) the largest disparities occurring due to restricted alignment accuracy are usually substantially smaller than the foveal diplopia thresholds; (c) interindividual variability in the magnitude of foveal diplopia thresholds is not only due to interindividual variability in the alignment accuracy; (d) the spread of foveal diplopia thresholds exceeds the spread of ocular alignment, which implies that the noise in the foveal disparity domain is not only due to the restricted alignment accuracy but also to sensory processes. Finally, the data confirm that, unlike the case with diplopia thresholds, the spread of stereoscopic thresholds is not affected by the restricted alignment accuracy.

INTRODUCTION

When an observer with normal binocular vision looks with both eyes at an object the eyes align with respect to the fixated part of the object in such a way tha the images in the foveae of the two eyes fall on nearly corresponding retinal locations.

Ocular alignment is however not perfect which results in residual dispari-

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ties called *fixation* disparities. These fixation disparities are of special interest because they have to be tolerated sensorially if binocular single vision is to be maintained.

The purpose of the present study was to compare the size of the fixation disparities occurring during steady binocular fixation with the foveal diplopia threshold (i.e. the value of the retinal disparity at which binocular single vision ends).

The data available in the literature on the accuracy of ocular alignment during steady binocular fixation show large differences: the reported standard deviations (SD) of this accuracy vary between 1'[1)] and 8' (Riggs and Ratliff, 1951: SD<1'; Ditchburn and Ginsborg, 1953 and Krauskopf, Cornsweet and Riggs, 1960: SD = 1.9' - 2.5'; Fender and Julesz, 1967: SD = 7' - 8'). This implies that the maximum fixation disparities occurring during steady binocular fixation which have to be tolerated sensorially if binocular single vision is to be maintained vary between 2' and 20' (2 - 3 times SD) in different studies.

A large variability in the literature is not only found for the reported accuracy of ocular alignment but also for the reported foveal diplopia thresholds (see e.g. Duwaer and Van den Brink, 1981).

Because of these variabilities, the comparative magnitudes of fixation disparities and foveal diplopia thresholds can only be analysed properly when they are both obtained *in the same subjects and under the same stimulus conditions.*

In the literature, data of this kind have only been gathered with a rather restricted accuracy for one subject, the quantity being measured the horizontal disparity (Palmer, 1961). These data suggest that the foveal diplopia threshold for horizontal disparity is substantially larger than the largest horizontal fixation disparities due to the restricted accuracy of ocular alignment. It is worth noting that this would imply a discrepancy between the minimum sensory tolerance to horizontal disparities needed to maintain binocular single vision given the accuracy of ocular alignment on the one hand, and the actual sensory tolerance measured on the other.

In the present study additional data will be provided and analysed concerning the comparative magnitudes of fixation disparities and foveal diplopia thresholds during steady binocular fixation for both horizontal and vertical disparities.

The distributions of fixation disparities were determined by a subjective alignment method in which the subject had to judge the alignment of two dichoptic nonius lines (see e.g. Ogle, Mussey and Prangen, 1949 and Ogle and Prangen, 1953).

METHODS

Stimulator

The stimuli were presented in an electronic stereoscope consisting of a white background screen (diameter 15°, mean luminance level 3 cd/m^2) and two XYZ displays (the preliminary experiments, the results of which are presented in Fig. 3 used HP 1321A XYZ displays with white P31 phosphor; the other experiments used Philips PM 3233 oscilloscopes with green P31 phosphor). The displays were viewed dichoptically through two beam splitters positioned directly in front of the subject's eyes and adjusted so as to present the two displays in the same direction at a fixation distance of 105 cm. The luminance of the stimuli on the displays was adjusted to 1.8 log unit above the (contrast) threshold for perception of the stimulus. The line width of the stimuli amounted to 0.3 mm (1.0') for the Philips oscilloscopes and 0.35 mm (1.2') for the HP 1321A displays. The angular dimensions of the images on the two displays were equalized to within 0.3' while looking through the beam splitters with a telescope (magnification 30). The parameter in the experiments was the disparity between certain parts of the stimuli on the display screens. The magnitude of this disparity or separation on the displays had an accuracy of 0.1' and was controlled by a microprocessor and an 8-bit digital-to-analog convertor. The subject's head was immobilized with a bite-board.

Stimuli

The stimuli on the displays consisted of a continuously visible fixation stimulus and a test stimulus which was presented tachistoscopically with a duration of 200 msec unless otherwise specified.

Fixation stimulus: The data were collected for binocular fixation of the centre of a continuously visible fixation circle with a diameter of 1°. In addition, the orientation of the disparity was marked on the background screen with a black line interrupted in the central 1.5° where the stimuli on the display screens were presented [2].

Test stimuli: The test stimuli for the determination of *fixation disparities* (Fig. 1A and B) consisted of a pair of lines of length 15' and width 1.0'. These nonius lines were presented either to the same eye (monocular presentation) or to different eyes (dichoptic presentation). For the determination of *vertical fixation disparities* the nonius lines were horizontal (Fig. 1A). The monocular nonius lines (Fig. 1A, bottom) had a horizontal separation of 6' between the endpoints. The uncrossed horizontal disparity between the dichoptic nonius lines (Fig. 1A, top) was adjusted by the subjects in order to obtain a perceived horizontal separation of 6' between the endpoints. The uncrossed

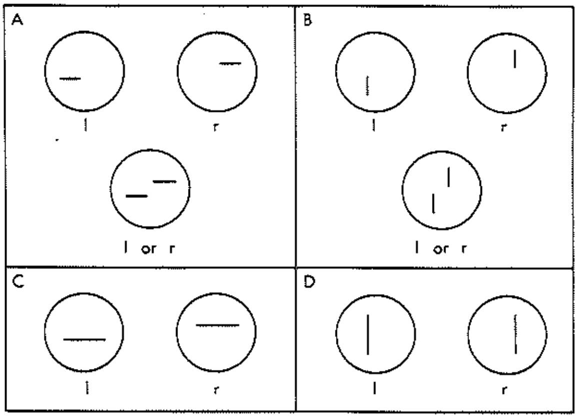

Fig. 1. Schematic representation of the foveal stimuli used in this study. The letters l and r stand for stimuli presented to the left and right eye respectively.

horizontal disparity between the dichoptic nonius lines (Fig. 1A, top) was adjusted by the subjects in order to obtain a perceived horizontal separation of 6' between the endpoints. The horizontal nonius lines were presented with different vertical displacements by varying the vertical separation between the monocular nonius lines or the vertical disparity between the dichoptic nonius lines. For the determination of *horizontal fixation disparities* the same stimuli were used, but rotated through 90° (Fig. 1B). The only perceptible difference between dichoptically and monocularly presented nonius lines, apart from the degree of misalignment, was that the perceived lateral separation between the end-points of dichoptically presented nonius lines was different in successive presentations as a result of varying fixation disparities [3]. The test stimuli for the determination of *diplopia thresholds* consisted of a pair of lines of length 30' and width 1.0'. The thresholds for vertical disparity were determined with horizontal test lines (Fig. 1C) and the thresholds for horizontal disparity with vertical test lines (Fig. 1D).

Classification of fixation disparity assessments (see Fig. 2A)

For the *horizontal* nonius lines, the subject was asked to judge whether the right-hand nonius line was displaced downwards with respect to the left-hand one ('negative displacement','↓'), displaced upwards ('positive displacement', '↑'), or whether the two nonius lines were in line ('no displacement', 'o'). For the *vertical* nonius lines, the subject was similarly asked to judge whether the upper one was displaced to the left of the lower one ('negative displacement', '↓'), displaced to the right ('positive displacement', '↑'), or whether the two were in line ('no displacement', 'o'). The classification 'no displacement' was used to avoid a possible bias resulting from an asymmetrical classification of doubtful displacements, and to avoid confusion of the effects of a

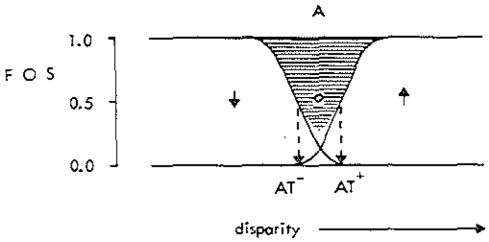

Fig. 2A. Classification of fixation disparity assessments. Schematic representation of the frequency of seeing (FOS) 'negative displacement' ('↓') and 'positive displacement' ('↑') between a pair of nonius lines as a function of the separation or disparity level in a classification procedure with 'no displacement' ('o') as the third possible category.

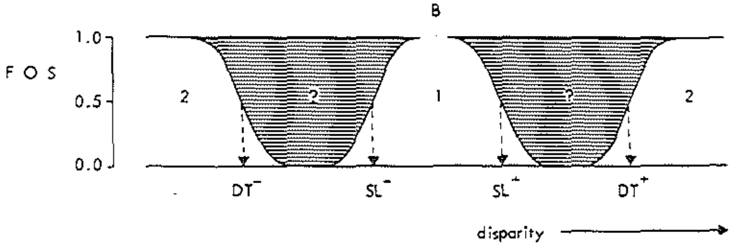

Fig. 2B. Classification of diplopia threshold assessments. Schematic representation of the frequencies of seeing (FOS) 'unequivocal singleness' ('1') and 'unequivocal doubleness' ('2') as a function of the separation or disparity level in a classification procedure with 'neither 1 nor 2' as the third possible category ('?').

rise in the threshold and in the noise level (see *Results and discussion: Alignment data*). The frequencies of seeing these 3 percepts ('FOS' values) were determined as a function of the physically induced displacements, with 40 - 80 trials at each displacement value. The subjects were not specially forced to use the sharpest possible criterion for 'positive displacement' or 'negative displacement' in contrast to typical practice during the assessment of vernier acuity using a 2-alternative forced-choice procedure.

Classification of diplopia threshold assessments (see Fig. 2B)

The subjects were asked to classify the percepts of the test stimulus as 'unequivocally single' (denoted by '1' from now on), 'unequivocally double' (denoted by '2'), or 'neither unequivocally single nor unequivocally double' (denoted by '?'). They were also asked to give a verbal description of the percepts they assigned to the last-mentioned class.

Unequivocal doubleness was defined as the perception of two lines with a separation between them. Unequivocal singleness was defined as the percept of the test stimulus without disparity. For *presentation times of 200 msec*, the test stimulus without disparity was always seen as a sharp line, not broadened, not restless and displaced. However, for *20 msec presentation times* the line perceived was regularly broadened, blurred and 'restless' as though the stimulus contained a disparity. The subjects were instructed *not* to incorporate these percepts in a new definition of singleness, but to classify them as transitional percepts ('?'). FOS values for these 3 percepts were determined as a function of the disparity, with 40-80 trials at each disparity value.

Calculation of the thresholds

The FOS curves obtained were fitted by a convolution of normalized Gaussian noise and 3 hypothetical disparity ranges, in each of which one of the three possible percepts ('1', '?' or '2', see Fig. 2B, or '↓', 'o' or '↑', see Fig. 2A) is always seen. Each (abrupt) transition between neighbouring regions is defined as a 'threshold', with the standard deviation of the fitted Gaussian noise as its standard deviation. This implies that the thresholds were calculated under the assumption that at each disparity one of the three possible percepts is always seen, but that the effective locations of the transitions between the different possibilities vary due to intrinsic additive Gaussian noise. It may be noticed in Fig. 2 that the above-mentioned convolution simply results in an integrated Gaussian distribution function (see the FOS curves for '↓', '↑', '1', '?' and '2' in Fig. 2) unless the separation between neighbouring transitions is small in comparison with the amount of noise (see the FOS curves for 'o', indicated by the boundary of the shaded area in Fig. 2A, and for '1' in Fig. 6).

The difference between the disparities or separations at which the lines are optimally aligned and those at which 'alignment' ends after deconvolution will be referred to as the '*alignment threshold*' ('AT') from now on, the threshold corresponding to the disparity at which unequivocal singleness ends the '*singleness limit*' ('SL') and the threshold corresponding to the disparity at which unequivocal doubleness begins the '*doubleness threshold*' ('DT'). Each of these thresholds has one value at positive values of the disparity (denoted by the suffix '+') and one value at negative disparities (denoted by the '-' suffix). The singleness limit and doubleness threshold may be regarded as lower and upper limits of 'the' diplopia threshold, while the mean fixation disparity 'F' as determined in this study is defined as the mean of AT^- and AT^+ for dichoptic nonius lines. The measure of the spread of F used in this study is described in *Results and discussion*: The distribution of fixation disparities.

Experimental procedure

The data were collected in sessions of 240 trials each. Each session lasted about 30-45 minutes with a rest period of at least 15 minutes between sessions. On a given day, 2 or 4 sessions were held. Sessions for the determination of fixation disparities were alternated by diplopia threshold sessions.

In each session the subject had to classify 12 different disparity values 20 times. He or she started each trial by pressing a button. After 0.5 sec the stimulus appeared with a constant disparity or separation which was selected at random by a microprocessor from 12 preselected values covering a sufficiently wide range to evoke any one of the possible percepts. The subject then classified the percept. Between successive stimulus presentations the subject had to look *attentively* at the fixation stimulus for at least 3 seconds.

Subjects

The data were obtained from 3 subjects (ALD, BdL and AEHP) who had already participated in a number of similar experiments.

The distribution of vertical fixation disparities and the vertical disparity thresholds were determined in subjects ALD, BdL and AEHP. For the determination of the distribution of horizontal fixation disparities, only subjects ALD and BdL participated, because subject AEHP was not longer available. All subjects were corrected for myopia (-0.75 D for both eyes for ALD, -3.25 D left eye and -3.00 D right eye for BdL and -4.75 D for both eyes for subject AEHP). In addition, subject AEHP used artificial pupils with a diameter of 2.5 mm. With these corrections, all monocular Landolt-C visual acuities were better than 5/4.

All subjects had good stereoscopic vision (≤ 30", TNO test, Lameris Utrecht, The Netherlands). The angular dimensions of the disparities and separations in the stimuli were corrected for the reduction (R) introduced by the negative spherical correction. A psychophysical experiment showed that R amounted to 2.2% per dioptre for the test spectacles used. The application of this correction implies that the angular dimensions specified are expressed in terms of corresponding angular rotation of the eyes for each subject.

PRELIMINARY EXPERIMENTS

Validity of the subjective alignment method for the determination of fixation disparity

First of all, the distribution of fixation disparities was determined with a subjective alignment method, in which the subject had to judge the alignment of two dichoptic nonius lines (see Fig. 1A, 1B and 3A). The perceived displacement for physically aligned dichoptic nonius lines is generally assumed to be equal to the objectively present fixation disparity. Hebbard (1962) has shown the validity of this assumption for *horizontal* fixation disparities by direct comparison with objective recordings of eye positions. Hebbard's data confirm the same conclusion that can be drawn from a comparison of objective measurements by Riggs and Niehl (1960) and 'subjective' measurements by e.g. Ogle, Mussey and Prangen (1949). Crone and Everhard-Halm (1975) have shown that the subjective method and an objective assessment also yield the same values for *cyclo* fixation disparities. The validity of this subjective method for small *vertical* fixation disparities has never been verified with objective recordings;

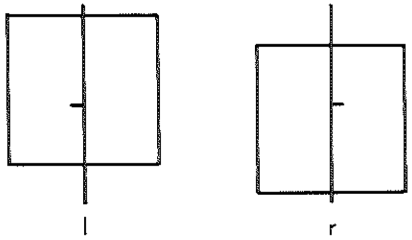

Fig. 3A. Schematic representation of the line stimuli used to obtain the data of Fig. 3B. The letters l and r stand for presentation to the left and right respectively.

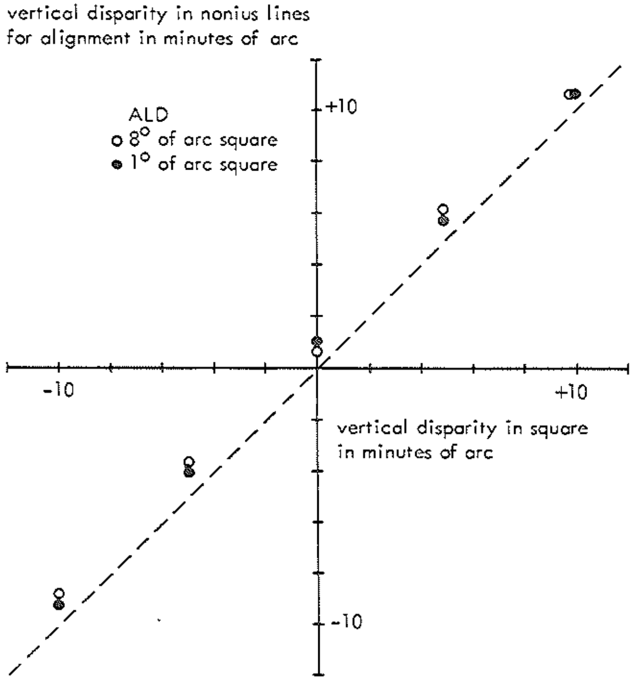

Fig. 3B. Test of validity of subjective alignment method for determination of fixation disparity. Vertical disparity to be introduced between the nonius lines in order to obtain optimum alignment, as a function of the vertical disparity between the squares. The standard errors (n=5) are smaller than the size of the symbols.

however, we did test it by means of a simple psychophysical experiment in which the subject (ALD) looked at the portion of a vertical fixation line (of length 10°) between two dichoptic nonius lines (of length 20') with a randomly chosen vertical disparity. The nonius lines were positioned at the centre of the vertical fixation line and of squares (of side 1° or 8°), the two squares being presented dichoptically with a certain amount of vertical disparity (see Fig. 3A). The subject was asked to adjust the vertical disparity in the nonius lines so that they became optimally aligned. The whole stimulus was then removed and again presented with other vertical disparities between the nonius lines and squares. The whole adjustment procedure was repeated to give five adjustments, for vertical disparities of ± 10', ± 5' and 0' between the squares. The mean values of the adjusted vertical disparities between the nonius lines are plotted in Fig. 3B as a function of the vertical disparity between squares of side 1° (solid circles) and 8° (open circles).

Inspection of Fig. 3B shows that, apart from an offset of about 0.9', the vertical displacement induced between the dichoptic nonius lines is equal to the vertical disparity between squares of side 1° and even 8°. It is highly unlikely that the displacement induced in the nonius lines is due to a sensory process as this would require interaction between the square and the, otherwise uncorrelated, nonius lines over distances in the visual field up to at least 4° with an accuracy of at least 1'. It is therefore concluded that the perceived vertical displacement between a pair of physically aligned dichoptic nonius lines is indeed equal to the vertical fixation disparity. This conclusion is supported by the fact that the observed variation with time of the relative vertical displacement of the nonius lines in response to abrupt presentation of vertical disparity closely resembles the variation of vergence eye-movements with time, as reported by Perlmutter and Kertesz (1978).

The apparent alignment of the eyes to stimuli with vertical disparities has previously been reported by e.g. Burian (1939) and Ogle and Prangen (1953).

Influence of stimulus presentation time

In nearly all the experiments described in the present paper we used tachistoscopically presented test stimuli with presentation times of 200 msec and random variation of the magnitude and sign of the disparity in successive presentations. This presentation time is short enough to prevent interference from fusional eye-movements under the applied stimulus conditions, as may be concluded from the finding that the diplopia threshold did not fall when the presentation time was decreased from 200 msec to 100 msec and from reported data on reaction times of fusional eye-movements which show that these movements, if they occur, start after about 0.2 sec and certainly not before 0.1 sec (Westheimer and Mitchell, 1956).

A presentation time of 200 msec is, however, not short enough to 'freeze' the eye-movements, i.e. to prevent displacements of the images of the test stimulus on the retinae due to involuntary eye-movements during presentation of the test stimulus. This can only be accomplished with much shorter presentation times. An important disadvantage of much shorter presentation times is, however, that they give foveal diplopia thresholds which can often be fully accounted for by monocular resolution, i.e. the effects of particular interest to us are completely eliminated under these conditions (Woo, 1974; Woo and Reading, 1978). This is confirmed by the results of some of our own experiments, presented in Fig. 6 and Table 2, using presentation times of 20 msec. The singleness limit for vertical disparity between dichoptic test lines (stimulus of Fig. 1C) then amounts to 1.4' (SD = 1.6') which is equal to the singleness limit for vertical separation between monocular test lines (stimulus of Fig. 1C, but with both horizontal lines presented to one eye) which amounts to 1.4' (SD = 0.5'). The dichoptic data just contain more noise.

When the involuntary eye-movements are not frozen, there will be some variation of the fixation disparity due to involuntary eye-movements with a stimulus presentation time of 200 msec. This variation was found to be so small that the subjects did not notice it, either during determination of diplopia thresholds or during the determination of the fixation disparity by the alignment method. It was, nevertheless, explicitly taken into account in the determination of both the diplopia thresholds and the distribution of fixation disparities by 'sampling' the fixation disparities with the test lines for 200 msec.

RESULTS AND DISCUSSION

The diplopia thresholds and alignment data determined using horizontal test lines with vertical disparity or separation are presented in Tables 1A and 2A, and those determined using vertical test lines with horizontal disparity or separation in Tables 1B and 2B.

Table 1A. Alignment data (in minutes of arc) for horizontal test lines with vertical separation or disparity.

subject	$AT\|_D \pm SD\|_D$	$AT\|_M \pm SD\|_M$	F*)	$SD\|_F$
ALD	0.6 ± 0.6	0.4 ± 0.25	+0.5	0.5
BdL	0.7 ± 0.6	0.4 ± 0.3	+0.4	0.5
AEHP	1.6 ± 1.2	0.6 ± 0.3	-0.7	1.2
ALD, 20 msec	0.5 ± 0.7	0.5 ± 0.25	+0.6	0.65

*) "+" = right eye points to a higher position than left eye
"-" = right eye points to a lower position than left eye

Table 1B. Alignment data (in minutes of arc) for vertical test lines with horizontal separation or disparity.

subject	$AT\|_D \pm SD\|_D$	$AT\|_M \pm SD\|_M$	F**)	$SD\|_F$
ALD	0.7 ± 1.6	0.5 ± 0.35	+5.0	1.6
BdL	1.1 ± 1.7	0.4 ± 0.3	+7.4	1.7
ALD, 20 msec	0.9 ± 1.6	0.5 ± 0.3	+5.6	1.6

**) "+" = eyes' convergence 'behind' the fixation stimulus

$AT|_D$ = dichoptic alignment threshold;
$SD|_D$ = standard deviation of $AT|_D$;
$AT|_M$ = monocular alignment threshold;
$SD|_M$ = standard deviation of $AT|_M$;
F = mean fixation disparity;
$SD|_F = \{(SD|_D)^2 - (SD|_M)^2\}^{\frac{1}{2}}$ = standard deviation of the distribution of fixation disparities.

Table 2A. Thresholds with standard deviations for vertical disparity (in minutes of arc).

subject	$SL^+ \pm SD$	T	$DT^+ \pm SD$	$SL^- \pm SD$	T	$DT^- \pm SD$
ALD	3.2 ± 0.9	1	5.0 ± 0.9	-1.4 ± 0.7	1	-2.9 ± 0.7
BdL	4.7 ± 1.4	1	9.5 ± 0.8	-5.5 ± 2.0	1	-9.9 ± 1.1
AEHP	4.6 ± 3.1	2	7.1 ± 1.8	-6.3 ± 1.9	2	-8.1 ± 2.3
ALD, 20 msec	2.0 ± 1.6	1	4.8 ± 1.4	-0.8 ± 1.6	1	-3.1 ± 1.6

SL = singleness limit;
T = transitional percept between SL and DT;
DT = doubleness threshold;
"+" = test line in stimulus for right eye higher than in stimulus for left eye;
"-" = test line in stimulus for right eye lower than in stimulus for left eye.
Transitional percepts (T) 1: broadening, blur, restlessness
2: subject not able to specify the percept

Table 2b. Thresholds with standard deviations for horizontal disparity (in minutes of arc).

subject	$SL^+ \pm SD$	T	$DT^+ \pm SD$	$SL^- \pm SD$	T	$DT^- \pm SD$
ALD	1.0 ± 0.5*)	2a	7.8 ± 2.2	-1.0 ± 0.5	2b	-5.7 ± 1.6
BdL	0.9 ± 0.6	2a	23 ± 3.3	-4.1 ± 2.0	1	-13.0 ± 2.4
ALD, 20 msec	6.7 ± 2.1	1	11.0 ± 2.1	+0.5 ± 2.1	1	-2.9 ± 2.5

SL = singleness limit;
T = transitional percept between SL and DT;
DT = doubleness threshold;
"+" = uncrossed horizontal disparity (equivalent to test line 'behind' the fixation stimulus);
"-" = crossed horizontal disparity (equivalent to test line 'in front of' the fixation stimulus).
Transitional percepts (T) 1 : broadening, blur, restlessness
2a: unequivocal singleness, image apparently behind fixation stimulus
2b: unequivocal singleness, image apparently in front of fixation stimulus

*) After a training period, subject ALD virtually lost the percept 'no depth' so that only the percepts 'in front' or 'behind' remained. A 2-alternative forced-choice procedure showed that this subject could then detect a disparity of 0.2' of arc 50% correctly.

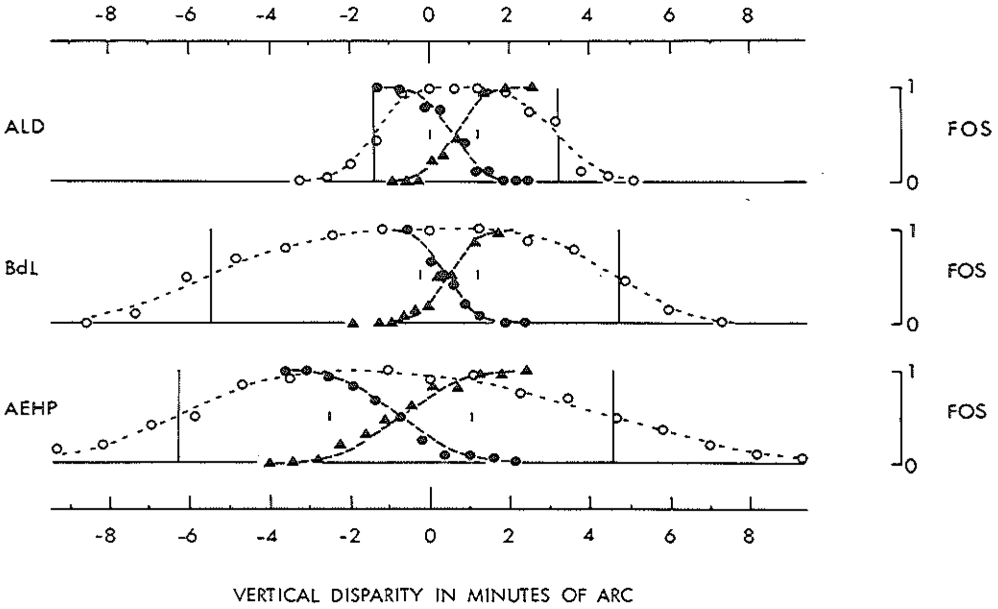

Fig. 4. Comparison of data on vertical fixation disparities (solid symbols) and diplopia thresholds (open circles) obtained from three subjects (ALD, BdL, AEHP) for 200 msec presentation of the horizontal nonius lines shown in the upper part of Fig. 1A and the horizontal test lines shown in Fig. 1C respectively.

A first impression of the comparative magnitudes of the foveal diplopia thresholds and the fixation disparities may be obtained by inspection of Fig. 4 and 5.

Fig. 4 displays the frequency of seeing unequivocal singleness obtained from three subjects (ALD, BdL and AEHP) as a function of the vertical disparity (open circles), for 200 msec presentation of the horizontal test lines shown in Fig. 1C. The long vertical lines indicate the corresponding singleness limits. The solid symbols represent frequencies of seeing upward displacement (solid triangles) and downward displacement (solid circles) as functions of the vertical disparity for 200 msec presentations of the horizontal nonius lines shown in the upper part of Fig. 1A. The broken and solid lines represent theoretical curves fitted to the experimental points as described in the *Methods* section. The FOS curve for upward displacement has been shifted to the left by $\frac{1}{2}(AT^{+} - AT^{-})$ and that for downward displacement to the right by the same amount so that the two shifted curves cross at the disparity level at

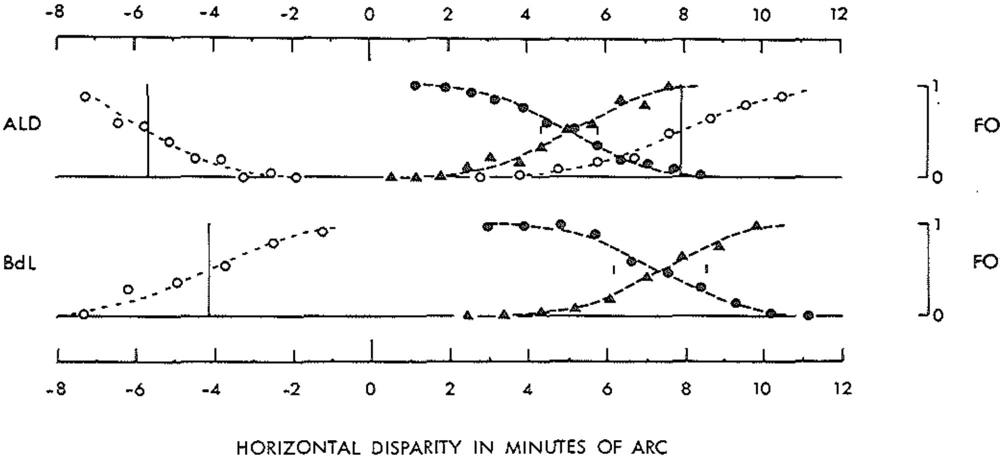

Fig. 5. Comparison of data on horizontal fixation disparities (solid symbols) and diplopia thresholds (open circles) obtained from two subjects (ALD and BdL) for 200 msec presentation of the vertical nonius lines shown in the upper part of Fig. 1B and the horizontal test lines shown in Fig. 1D respectively.

which the perceived alignment is optimum; AT^+ and AT^- are the positive and negative alignment thresholds, defined in Fig. 2A. The small vertical bar to the right of the crossing indicates the value of AT^+ and the one to the left the value of AT^-. The mean fixation disparity (F) is defined as the mean of AT^+ and AT^-; it thus lies half-way between these two vertical bars in the graph. The disparity values at which the shifted FOS curves for upward and downward displacements reach the value 0 and 1 define approximately the range of the vertical fixation disparity.

Fig. 5 displays the frequency of seeing unequivocal doubleness obtained from subject ALD and the frequency of seeing unequivocal singleness obtained from subject BdL, as functions of the horizontal disparity (open circles) for 200 msec presentation of the vertical test lines shown in Fig. 1D. In subject BdL the FOS for doubleness started to differ from zero at disparities that were too large to be shown in this figure (*cf*. Table 2B). The FOS curves shown represent the lowest transitions to deteriorated singleness observed. The long vertical lines in the upper part of the figure represent the doubleness thresholds, and the one in the lower part a singleness limit. The solid symbols represent frequencies of seeing displacements to the right (solid triangles) and to the left (solid circles) as a function of the horizontal disparity for 200 msec presentation of the vertical nonius lines depicted in the upper part of Fig. 1B. The FOS curves shown have been shifted in such a way that the extreme values of the horizontal fixation disparities correspond approximately to the disparity values at which the shifted FOS curves for perceived horizontal misalignments reach the values 0 and 1 (*cf.* discussion of Fig. 4).

The major conclusions which can be drawn from Fig. 4 and 5 are that the diplopia thresholds are substantially larger than the range of fixation disparities, that the vertical fixation disparities remain remarkably small, and that the vertical fixation disparities are much smaller than the horizontal ones.

We will now proceed to a more detailed analysis of the data. The magnitude of the diplopia thresholds as such will not be discussed, as this has already been done in a previous paper (Duwaer and Van den Brink, 1981).

Alignment data

It should be noted that the monocular alignment thresholds are not directly comparable with the vernier acuities. The monocular alignment threshold ('$AT|_M$') given in Table 1 corresponds to 'false alarm rates' - i.e. the rates at which physically negative displacements are classified as 'positive displacement' or vice versa - of 2% to 9%, whereas the vernier acuity is usually defined as the displacement that results in the much larger false alarm rate of 25% 4).

Inspection of Table 1 shows that the dichoptic alignment threshold ('$AT|_D$') tends to be larger than the corresponding monocular alignment threshold ($AT|_M$). This might indicate an effective threshold for the processing of displacements between dichoptic nonius lines which is not present in the processing of displacements between monocular nonius lines. The advantage of the classification we used in this study with 'undetermined displacement' as the third category besides 'positive displacement' and 'negative displacement' is that the slopes of the FOS curves for 'positive displacement' and 'negative displacement' do not decrease as a result of the threshold, as would be the case without the third category when the subject is not biased to use one of the two assessment criteria in case of undetermined displacements. This implies that the effect of a low threshold for the processing of dichoptic displacements will not be erroneously ascribed to an increased standard deviation of the underlying noise, i.e. variation of the fixation disparity.

The distribution of fixation disparities

The mean fixation disparity (F) equals the physical displacement that has to be introduced between the dichoptic nonius lines to obtain optimum dichoptic alignment. Inspection of Table 1 shows that the mean fixation disparity differs from zero. It amounts to 0.4' - 0.7' in the vertical direction and 5' - 7.4' in the horizontal direction 5).

The standard deviation of the distribution of fixation disparities ('$SD|_F$') can be estimated from that of the dichoptic alignment threshold ('$SD|_D$') by correcting the latter for the *intrinsic* inaccuracy of the dichoptic alignment task, i.e. the standard deviation that would have been obtained had the eyes remained perfectly aligned. The standard deviation of the monocular alignment threshold ('$SD|_M$') has been taken as a measure of this intrinsic inaccuracy 6). The correction has been performed under the assumption that the variability of the dichoptic alignment due to fixation disparities is statistically independent of the variability due to the intrinsic inaccuracy of the dichoptic alignment task, so that their variances $(SD)^2$ can simply be summed:

$$(SD|_D)^2 = (SD|_F)^2 + (SD|_M)^2 \text{ or } SD|_F = \{(SD|_D)^2 - (SD|_M)^2\}^{\frac{1}{2}}$$

The results of this calculation are given in Table 1. Inspection of this table shows that $SD|_F$ for vertical disparities amounts to 0.5' in subjects ALD and BdL, and to 1.2' in subject AEHP. $SD|_F$ for horizontal disparities amounts to 1.6' in subject ALD and 1.7' in subject BdL.

It should be remembered that these values were obtained with 200 msec sample times of the fixation disparity. The effect of this sample time is, however, not large. This is concluded from the alignment data obtained from subject ALD with 20 msec presentation time (see Table 1 and Fig. 6). The standard deviation for horizontal fixation disparities remained 1.6', while that for vertical fixation disparities increased from 0.5 to 0.65'.

It is concluded that *the accuracy of the vertical alignment of the eyes is*

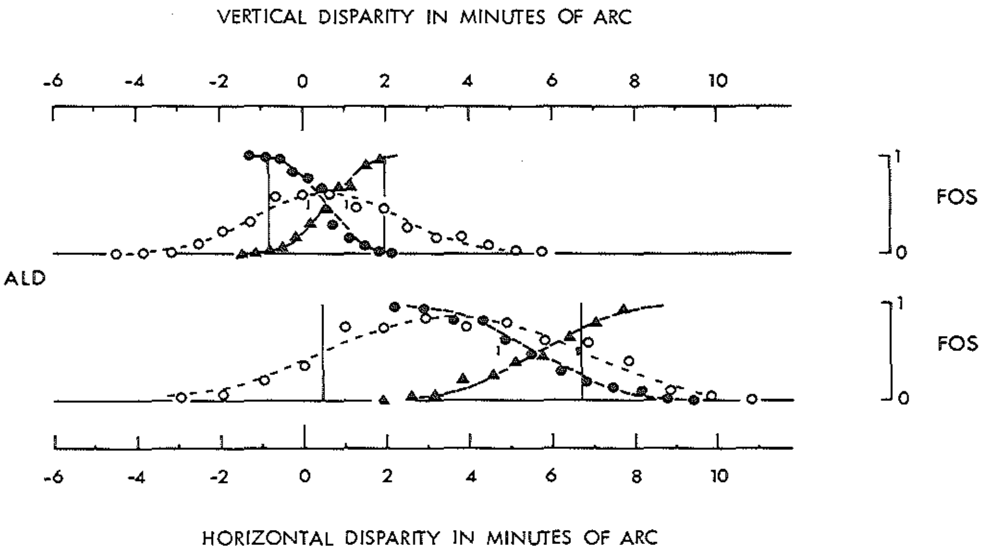

Fig. 6. Comparison of data on fixation disparities and diplopia thresholds in the vertical direction (top) and in the horizontal direction (bottom) obtained from subject ALD for 20 msec presentation of the nonius and test lines. For further details, see captions of Fig. 4 and 5.

remarkably good, and much better than the accuracy of the horizontal alignment. This can be understood if we recall that horizontal alignment can be influenced by voluntary control and the accomodation-convergence reflex, whereas vertical alignment cannot.

Comparison of diplopia thresholds and fixation disparities

The diplopia threshold has been compared with the fixation disparity by calculating the 'distance' between the mean disparity (F) of the eyes and the *lowest* thresholds marking a transition to deteriorated singleness, i.e. what we define as the singleness limit (SL) in this study. When this distance is expressed relative to the standard deviation ($SD|_F$) of the fixation disparity, a value of 2–3 might be expected, if the value of SL is critically adapted to the size of fixation disparities. As a result of the occurrence of fixation disparities, the internal representation of a stimulus without physical disparity will namely be a stimulus with disparities up to about $F - 2.5\ SD|_F$ and $F + 2.5$

$SD|_F$. Criteria for deteriorated singleness chosen at these disparity values would therefore lead to a useful interpretation of singleness given the intrinsic variability of singleness due to variable fixation disparities. However, the distances found are much larger than 2-3 $SD|_F$-units. For vertical disparities they amount to 3.8 - 5.4 in subject ALD, 8.6 - 11.8 in subject BdL and 4.5 - 4.8 in subject AEHP. Nevertheless, these diplopia thresholds do show critical adaptation to the overall amount of intrinsic noise present, as can be seen from the fact that these thresholds, expressed in terms of their own standard deviations, amount to 2.9 for subject ALD, 3.0 for subject BdL and 2.2 for subject AEHP. The diplopia thresholds for horizontal disparities are not critically adapted to the fixation disparity either: the distances in $SD|_F$-units found here amount to 1.8 - 6.7 in subject ALD and 6.8 - 9.2 in subject BdL.

It may thus be concluded that *the largest fixation disparities occurring due to restricted alignment accuracy are usually substantially smaller than the foveal diplopia thresholds obtained* with 0.2 sec presentation time. However, since the results of a previous study indicate that the foveal diplopia thresholds tend to fall when the presentation time is increased beyond 0.2 sec (Duwaer and Van den Brink, 1981), the discrepancy between the actual diplopia threshold and the minimum diplopia threshold needed to maintain binocular single vision given the accuracy of ocular alignment might become smaller for continuous observation of the test stimulus.

Inspection of Tables 1 and 2 also shows that the diplopia thresholds of the subjects BdL and AEHP are larger than those of subject ALD, while only the fixation disparities of subject AEHP are larger than those of subject ALD. It follows that *the interindividual variability in the foveal diplopia threshold cannot always be ascribed to interindividual variability in the fixation disparity.*

The influence of fixation disparities on the spread of disparity thresholds

The standard deviations of stereoscopic disparity thresholds based upon the appearance of relative depth (0.5' - 0.6', see Table 2) are much smaller than those of the horizontal fixation disparity (1.6' - 1.7', see Table 1).

This finding confirms that the accuracy of stereoscopic disparity thresholds is not influenced by variation in the fixation disparity due to involuntary eye-movements.

This is, however, hardly surprising when we remember that fixation disparities do not introduce *relative* disparity which could interfere with the perceived relative depth (stereopsis). At most, fixation disparities could be expected to interfere with perceived *absolute* depth. However, perceived absolute depth is apparently also subject to a process of sensory stabilization of the outside world, just like absolute position: the things we see do not appear to move around, when the totality of images on the retina shifts due to eye-movements.

Our data support the conclusion that the accuracy of disparity thresholds based upon the perception of singleness and doubleness, i.e. diplopia thresholds, is restricted by the variability of the fixation disparity. However, *this is not the only factor involved,* as can be inferred from the finding that the standard deviations of the diplopia threshold are systematically larger than the corresponding standard deviations of the fixation disparity.

Sensory noise in the disparity domain

The finding that the standard deviation of the diplopia threshold is systematically larger than that of the fixation disparity implies that *the sensory processes underlying the diplopia thresholds also introduce a substantial amount of noise in the foveal disparity domain.* Assuming statistical independence of fixation disparity and sensory noise, the standard deviation of the latter can be calculated from that of the diplopia threshold. The results of this calculation show that the mean standard deviation of the sensory noise amounts to 0.6' for vertical disparities and 1.0' for horizontal disparities in subject ALD, 1.2' for vertical disparities and 2.0' for horizontal disparities in subject BdL, and 2.0' for vertical disparities in subject AEHP.

The results obtained in subject ALD with presentation times of 20 msec show that the foveal sensory noise increases when the presentation time of the test stimulus is reduced. It has been shown in a previous study (Duwaer and Van den Brink, 1981) that the sensory noise also increases outside the fovea.

Retinal stimuli during the determination of diplopia thresholds

The observed range of fixation disparities provides us with information about the stimuli present on the retinae during the determination of diplopia thresholds.

The most prominent transformation of the physical stimulus during its passage to the retinal stimulus apart from the above-mentioned introduction of noise, is the addition of an overall mean horizontal disparity shift of 5' - 7.3'.

The effect of this overall horizontal disparity will be small for the diplopia thresholds for vertical disparity, since the test stimulus consisted of horizontal lines that will only be affected effectively by horizontal disparity near the end-points.

The overall horizontal disparity shift can, however, be expected to have a large effect on the diplopia threshold for horizontal disparity, since it provides the subject with conflicting cues about the presence of horizontal disparity. A test stimulus without relative physical disparity still leads to a retinal image with substantial absolute disparity. Conversely, a retinal stimulus without absolute disparity is only produced by a non-zero relative physical disparity. Moreover, an increase in absolute retinal disparity could indicate either an increase or a decrease in relative physical disparity. It seems evident that the occurrence of these conflicting cues is responsible for the large difference between the diplopia thresholds for crossed and uncrossed *retinal* disparities in subject ALD (see Fig. 5). It should be noted that the evident effect of relative disparity on the magnitude of the singleness limit and doubleness threshold is not necessarily conveyed by relative depth, as the asymmetry also occurred at 20 msec presentation times when relative depth was only rarely perceived (see Fig. 6 and Table 2B). The observed interference of relative disparity with the magnitude of diplopia thresholds based upon absolute disparity is in agreement with earlier findings of interference of surrounding stimuli with the conspicuity of an absolute disparity (Duwaer and Van den Brink, 1981).

CONCLUSIONS

-The foveal diplopia thresholds were found to be substantially larger than the minimum diplopia thresholds needed to maintain binocular single vision given the accuracy of ocular alignment.

-Interindividual variability in the foveal diplopia threshold was found to be not always caused by interindividual variability in the size of fixation disparities.

-The accuracy of vertical alignment of the eyes is remarkably high which implies that there is hardly any need for sensory tolerance to foveal vertical disparities.

ACKNOWLEDGEMENTS

We would like to thank G.J. van der Wildt, A.E.H. Peters and C.M.M. de Weert for helpful discussions, C.J. Keemink and J.B.P. van Deursen for their technical assistance, R.H. Bathgate for improving the English, and the Netherlands Organization for the Advancement of Pure Research (ZWO) for financial support.

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NOTES

1. In this paper, all angular measures will be expressed simply in degrees ($^{\circ}$) or minutes (') without the qualification "of arc" each time.

2. For the determination of vertical fixation disparities in subject BdL, the line on the background screen had to be extended to the centre in order to prevent sensory fusion of the pair of dichoptic nonius lines. This extension did not change the effective fixation stimulus, as may be concluded from the observations that his mean horizontal fixation disparity remained the same (7' - 8') and that his eyes remained vertically aligned to the fixation circle when a physical vertical disparity was introduced in the circle and not in the line. Moreover, data obtained in subject ALD with and without the intersecting vertical line did not reveal any influence of this factor on the distributions of vertical fixation disparities obtained.

3. The effect of variation of the lateral separation of the end-points of dichoptically presented nonius lines due to varying fixation disparities can be neglected. This is concluded from the results of an experiment in which the relevant data (alignment thresholds and standard deviation) were gathered for monocularly presented horizontal nonius lines with lateral horizontal separations between 2' and 10'. In this range, which is about equal to the range of effective separations due to horizontal fixation disparities, the relevant data do not deviate more than 10% in subject ALD and 25% in subject AEHP from the data for a separation of 6'.

4. With the usual assumption of Gaussian distribution functions, we can calculate the equivalent vernier acuity that would result in the same false alarm rate at the displacement $AT|_M$ as the false alarm rate determined by $AT|_M \pm SD|_M$. These equivalent vernier acuities amount to 0.15' - 0.25' or 10" - 15". These values are comparable with those reported for stimuli on XYZ displays by other authors (e.g. Westheimer and Hauske, 1975).

5. Additional experiments showed that the value of the mean horizontal fixation disparity may fall (in some subjects) when the fixation marker also stimulates the foveola. In subject ALD, for instance, the mean horizontal fixation disparity then amounted to +1' (and the standard deviation of the fixation disparity to 1.4').

6. It is noteworthy that the dichoptic alignment thresholds are larger than the monocular alignment thresholds. The choice of the monocular standard deviation as an estimate of the dichoptic standard deviation that would be found without fixation disparities therefore implies the assumption that the difference between the dichoptic and monocular alignment thresholds is not accompanied by a substantial difference in the size of the intrinsic accuracies.

3.2 DIPLOPIA THRESHOLDS AND THE INITIATION OF VERGENCE EYE-MOVEMENTS

A.L. Duwaer and G. van den Brink*

ABSTRACT

The performance of the sensorimotor system which controls vertical vergence eye-movements has been compared with the psychophysical assessment of vertical disparities for eccentricities of up to 4^o in the visual field.

The major findings are: (a) vergence eye-movements can be initiated by vertical disparities that are much too small to induce diplopia, (b) the sensorimotor system is more sensitive than the sensory system which controls the psychophysical assessment of vertical disparity.

It is concluded on the basis of these findings that binocular single vision in spite of vertical disparities is primarily accomplished by the sensorimotor system which eliminates these disparities with a more than sufficient accuracy.

INTRODUCTION

Binocular single vision is accomplished by mutual alignment of the eyes with respect to a binocularly observed stimulus and by sensory tolerance for remaining retinal disparities. The necessary alignment of the eyes is achieved via the reflex action of vergence eye-movements in response to retinal disparities. Of special interest in this connection are the disparities that are too small to initiate vergence eye-movements, since they must be tolerated sensorially if binocular single vision is to be maintained. The purpose of the present study was to measure the smallest disparities that initiate vergence eye-move-

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ments and to compare them with the smallest disparities that result in diplopia (i.e. disruption of binocular single vision) and the smallest disparities that can be detected by the sensory system which controls the assessment of singleness of binocular vision.

This study extends the analysis given in a previous study of the relation between the sensorimotor system controlling vergence eye-movements and the sensory system controlling the psychophysical assessment of disparities (Duwaer and Van den Brink, 1981b). This earlier study was based on comparison of foveal diplopia thresholds and the accuracy of alignment of the eyes during continuous observation of a fixation stimulus.

The relation between the sensory system and the sensorimotor system is analysed here on the basis of threshold data obtained in a yes-no psychophysical procedure (Experiment 1) commonly used to determine diplopia thresholds, and threshold data obtained in a discrimination task (Experiment 2) which is ideal for the determination of detection thresholds. Stimuli with vertical disparity were used in this study because vergence eye-movements in response to vertical disparity are not subject to interference from voluntary control and the accommodation-convergence reflex as may be the case for vergence eye-movements in response to horizontal disparity (Ellerbrock, 1949; Ogle and Prangen, 1953; Crone, 1973; Houtman, 1979), and to avoid interference from stereoscopic depth effects. The data for the present study were collected for a situation in which the sensorimotor system controlling vergence eye-movements was allowed ample time to operate (2 sec), while the visual stimuli with disparity which were presented were of adequate contour length. These experimental conditions were chosen to eliminate the effect of spurious stimuli in the visual field that could also activate the sensorimotor system, to allow for the slowness of vergence eye-movements in response to vertical disparities (Perlmutter and Kertesz, 1978) and to simulate day-to-day visual conditions reasonably closely.

The occurrence of vergence eye-movements in response to vertical disparity was determined by a subjective alignment method in which the subject had to judge the alignment of two dichoptic nonius lines. The perceived misalignment for physically aligned nonius lines is generally accepted to be equal to the misalignment of the eyes (e.g. Hebbard, 1962; Ogle, 1964; Duwaer and Van den Brink, 1981b).

EXPERIMENT 1. DIPLOPIA THRESHOLDS AND THRESHOLDS FOR INITIATION OF VERGENCE EYE-MOVEMENTS

Introduction

The purpose of this experiment was to determine the smallest disparities that initiate vergence eye-movements in response to vertical disparity and to compare them with the smallest disparities that induce diplopia. The data were collected under similar stimulus conditions using the same psychophysical yes-no procedure and the same analysis of data.

Methods

Stimulator. The experiments were carried out in an electronic stereoscope consisting of two HP 1321A XYZ displays (white P31 phosphor) mounted 105 cm from the subject's eyes with a white background (mean luminance level 3 cd/m^2; dimensions 15° x 15° [1])). The luminance of the stimuli was adjusted to 1.8 log units above the (contrast) perception threshold. The line width of the stimuli amounted to 0.35 mm or 1.2'. For equalization of the angular dimensions of the images on the two displays to within an accuracy of 0.3', the images were viewed through the beamsplitters via a telescope (magnification 30). The parameter in the experiments was a disparity or separation between parts of the stimuli on the displays. The amount of disparity or separation was controlled by a microprocessor and an 8-bit digital-to-analog convertor with an accuracy of 0.1'. The subject's head was immobilized with a bite board.

Stimuli, psychophysical measuring procedures and calculation of thresholds. (i) Thresholds for the initiation of vergence eye-movements. The method used for the determination of the smallest disparities initiating vergence eye-movements is shown in Fig. 2A. The subject initially looked at the centre of a fixation stimulus consisting of a binocularly presented vertical line and a binocularly presented horizontal line; the latter had a gap of width 1° in the middle, where a pair of dichoptic nonius lines were presented. The relative position of these nonius lines, which reflects the relative position of the two eyes, is not constant but varies in time with excursions of up to 0.5'-1.0' as a result of involuntary eye-movements.

The mean vertical displacement between these lines was adjusted by the subject to zero. The subject then called up the test stimulus by pressing a button. After 0.5 sec the horizontal line was replaced for 2 sec by a pair of dichoptic squares with vertical disparity [2]). The subject was asked to judge whether the right-hand line appeared to shift upwards, downwards or not at all in response to the presentation of the pair of squares. The classification 'no

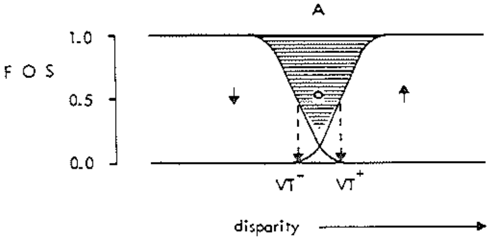

Fig. 1A. Schematic representation of the frequency of seeing (FOS) downward shift ('↓') and upward shift ('↑') of one of a pair of dichoptic nonius lines as a function of the disparity level when the FOS is determined in a classification procedure with 'no shift' ('o') as the third possibility. These FOS values are used to calculate the threshold for the initiation of vergence eye-movements in response to negative disparity (VT^-) and positive disparity (VT^+).

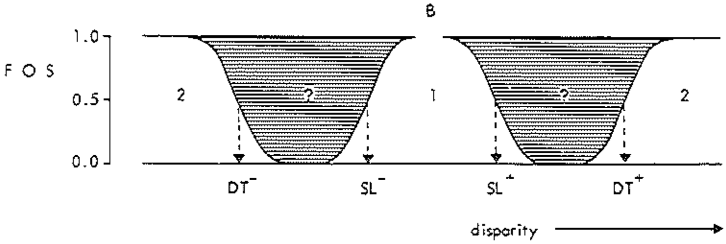

Fig. 1B. Schematic representation of the frequency of seeing (FOS) unequivocal singleness ('1') and unequivocal doubleness ('2') as a function of the disparity level when the FOS is determined is a classification procedure with 'neither 1 nor 2' (represented by '?') as the third possibility. These FOS values are used to calculate the singleness limits (SL^- and SL^+) and the doubleness thresholds (DT^- and DT^+).

shift' was to be used only when there had not been the slightest indication of an upward or downward movement. Upward or downward shift of the nonius lines would indicate the occurrence of vergence eye-movements, while the absence of shift would indicate that no vergence eye-movements were initiated. The frequencies-of-seeing (FOS) upward shift ('↑'), downward shift ('↓') and no shift ('o') were determined for random variations in the vertical disparity in successive presentations of the pair of squares. This was done in sessions in which the disparity was selected at random by a microprocessor from an appro-

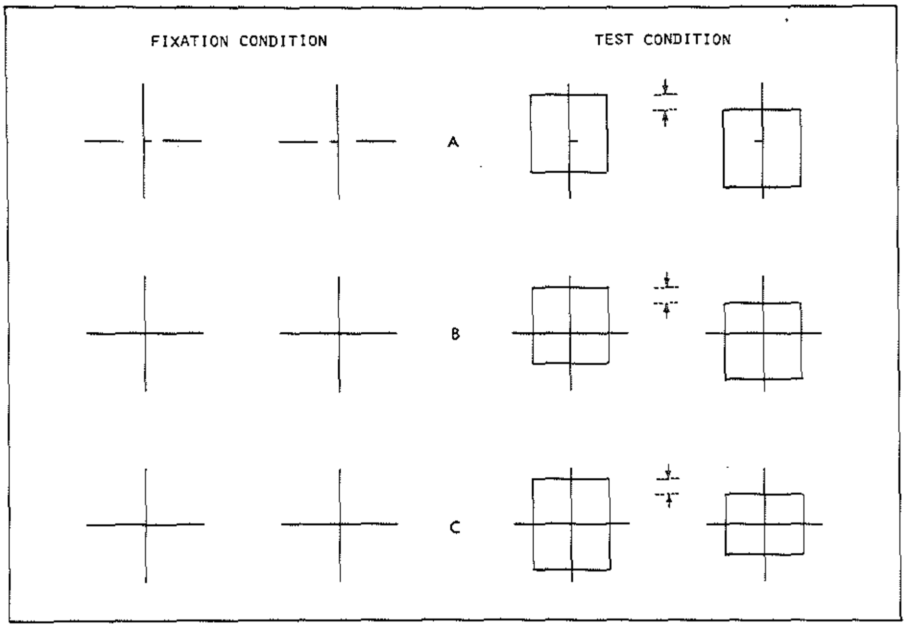

Fig. 2. Schematic representation of the stimuli presented to the left and right eye to initiate vergence eye-movements (A) and for the determination of diplopia thresholds (B and C). The fixation cross measured $10^\circ \times 10^\circ$. In (A) the horizontal arms of the cross were interrupted by a central gap of width 1°, where a pair of dichoptic nonius lines each 20' in length were presented. The stimuli were squares of side 1, 2, 4 and 8°. The squares embodied either an overall vertical disparity (A and B) or an aniseikonic vertical disparity (C). A stimulus with disparity of opposite sign is obtained when the stimulus for the left eye is presented to the right eye and vice versa. The magnitude of the disparity is indicated by arrows. The subjects were instructed to look at the centre of the fixation cross or in between the two nonius-lines.

priate number of preselected values (varying from 12 to 36 in different sessions, to suit the experimental conditions) so as to evoke all possible percepts. Each disparity value was presented 20 times.

The FOS curves obtained for upward and downward shifts (see Fig. 1A) were used to calculate the 'thresholds' for the initiation of vergence eye-movements (denoted by 'vergence thresholds' or 'VT' from now on) and their standard deviations. All thresholds and SD were calculated from FOS values between 0 and 1 for at least 4 different disparities. For the purposes of this calculation, a measured FOS curve (e.g. for upward shift, see Fig. 1A) was assumed to be an integrated Gaussian distribution function constructed by convolution of normalized Gaussian noise and an abrupt transition from FOS = 0 (e.g. no upward

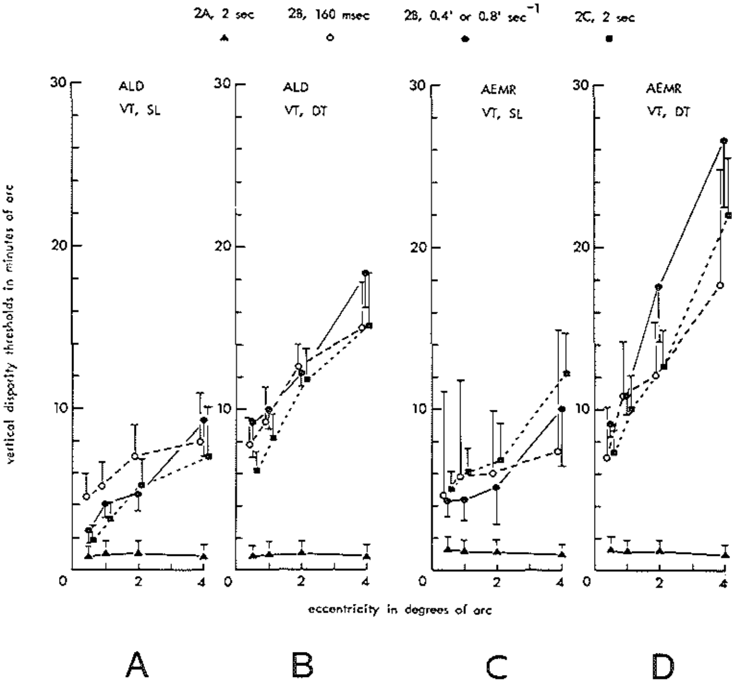

Fig. 3. Various thresholds for vertical disparity, plotted as functions of the eccentricity of the horizontal sides of the squares with vertical disparity. The thresholds for the initiation of vergence eye-movements (VT) for 2-sec presentation of overall vertical disparity (stimulus of Fig. 2A) are indicated by solid triangles, the diplopia thresholds obtained with 160-msec presentation of overall vertical disparity (stimulus of Fig. 2B) by open circles, the diplopia thresholds obtained with slowly changing overall vertical disparity (stimulus of Fig. 2B) by solid circles and the diplopia thresholds obtained with 2-sec presentation of aniseikonic vertical disparity (stimulus of Fig. 2C) by solid squares. The singleness limits (SL: A and C) and the doubleness thresholds (DT: B and D) were obtained from the highly practised subject ALD (A and B) and from the untrained subject AEMR (C and D). The length of the vertical bars is equal to the SD for the threshold in question.

shifts at all) to FOS = 1 (e.g. always an upward shift). The disparity at which this transition occurs was defined to be the threshold (i.e. VT^+ in the present example) with the SD of the fitted Gaussian noise as its SD. The SE of the thresholds are a factor 5 smaller than these SD. The means of VT^- for downward displacement and VT^+ for upward displacement for squares of side 1, 2, 4 and 8° are plotted in the Figs. 3A, 3B, 3C and 3D as solid triangles, as a function of the eccentricity of the horizontal sides of the squares with vertical disparity.

(ii) Diplopia thresholds. In order to compare thresholds for the initiation of vergence eye-movements with the diplopia thresholds that would have been found if vergence eye-movements had not occurred, we had to change the stimulus conditions so as to prevent vergence eye-movements from influencing the diplopia thresholds. This was done by extending the horizontal fixation line into the central 1° gap and keeping it continuously visible and by presenting the squares in one of the three following ways:

(a) Tachistoscopically, with presentation times of 160 msec which is less than the reaction time of vergence eye-movements (Westheimer and Mitchell, 1956) and less than the 2-sec presentation time used for the determination of vergence thresholds (see Fig. 2B).

(b) Continuously, with a gradual change in the vertical disparity of 0.4'/sec for the 1 and 2° squares and (in order to speed up the experiment) of 0.8'/sec for the 4 and 8° squares (see Fig. 2B). Under these conditions the horizontal fixation line was found to be capable of preventing vergence eye-movements in response to the vertical disparity in the squares. It may be noted that the presentation time in this mode is greater than the value of 2 sec used for the determination of vergence thresholds.

(c) Tachistoscopically, with the same presentation time (2 sec) as for the determination of vergence thresholds. Interference from vergence eye-movements was avoided in this case by presenting the disparities in the upper and lower sides of the squares not with the same sign (resulting in 'overall' vertical disparity; see Fig. 2B) but with opposite signs (resulting in 'aniseikonic' vertical disparity; see Fig. 2C). When the subject looks at the centre of the squares with aniseikonic vertical disparity, vergence eye-movements do not occur at all in response to the disparity in the horizontal sides. Qualitative observations indicated that the percept of a pair of squares with overall vertical disparity did not differ from that of the same pair of squares with aniseikonic vertical disparity.

The subject was asked to look at the centre of the fixation stimulus and to classify the percept evoked by the pair of squares (see Fig. 1B) as either unequivocally single ('1': the perceived square shows no disparity), unequivocally double ('2': two overlapping squares with a separation between the corresponding horizontal sides) or neither of these ('?': one square is seen, the horizontal sides of which exhibit blurring, broadening, 'restlessness' and percepts resembling those found in binocular rivalry). In the cases with tachistoscopic presentation (a) and (c) above the frequencies of seeing unequivocal singleness (1), unequivocal doubleness (2) and neither unequivocal singleness nor unequivocal doubleness (?) were determined with random variation in the vertical disparity in successive presentations as described above for the determination of the vergence thresholds. When the test stimulus was presented continuously, the FOS values were determined in 20 runs with a gradual increase in disparity and in 20 runs with a gradual decrease in disparity, while the subject looked at the central 1° of the horizontal fixation line, varied the fixation position slightly in order to prevent fading of the dichoptic squares and kept pressing a button as long as the percept of the squares was neither unequivocally single nor unequivocally double.

The FOS curves obtained for unequivocal singleness and unequivocal doubleness (see Fig. 1B) were used to calculate upper and lower limits for 'the' diplopia threshold, and their SD. All thresholds and SD were calculated from FOS values between 0 and 1 for at least 4 different disparities, on the assumption that the observed FOS curves for singleness and doubleness are convolutions of normalized Gaussian noise and hypothetical regions of disparities where one of the three image classes is always seen. The disparity at which unequivocal singleness ends after deconvolution will be called the singleness limit ('SL': see Fig. 1B) and the disparity at which unequivocal doubleness starts the doubleness threshold ('DT': see Fig. 1B) from now on. The thresholds plotted in Fig. 3 are the means of those obtained at positive and negative disparities and (in the case of continuous presentation of the stimulus), also the means of the thresholds obtained with increasing and decreasing disparity. The SE of the thresholds are a factor 5 less than the SD. The thresholds obtained with 160-msec presentation of squares with overall vertical disparity are indicated in Fig. 3A, 3B, 3C and 3D by open circles, those obtained with continuous presentation of squares with overall vertical disparities are represented by solid circles and those obtained with 2-sec presentation of squares with aniseikonic vertical disparity by solid squares.

Results and discussion

The data presented in Fig. 3A and B were obtained from a highly practised subject (ALD, one of the authors, corrected myope: left and right eye -0.75D [3]) and those in the Figs 3C and 3D from a subject without any training in the performance of such visual tasks (AEMR, emmetropic).

The threshold for the initiation of vergence eye-movements (VT) is plotted in Fig. 3A, B, C and D (solid triangles) as a function of the eccentricity of the sides of the square with disparity. It will be seen that this threshold is roughly constant at 1' for all eccentricities, with a SD of less than 0.8'. It is noteworthy that the centre of the region bounded by VT^- and VT^+ lies at the non-zero disparity of -0.8' (square presented to right eye 0.8' lower than that for left eye) for subject ALD and of -0.5' for subject AEMR, indicating that the sensorimotor system operates with reference to small non-zero fixation disparities. The remarkably small value of the vergence thresholds agrees with the finding of Burian (1939) that the eyes can align to stimuli at eccentricities of up to 12° in the visual field. Comparison of the vergence threshold and its SD shows that the region of disparities bounded by VT^- and VT^+ where the subject did not see disparity-induced changes in the alignment of the nonius lines is of the same order of magnitude as the accuracy with which this region can be determined. It should be remembered that this accuracy is primarily limited by the difficulty of recognizing a disparity-induced upward or downward shift in the nonius lines because of the continuously changing relative position of these lines (with excursions of up to 0.5'-1.0') as a result of involuntary eye-movements. It is therefore not necessarily true that the occurrence of a region where a disparity-induced change in the alignment of the eyes is not seen would imply the existence of a region of disparities that do not activate the sensorimotor system. The actual threshold (VT) in the sensorimotor system might be zero, which would mean that the elimination of disparities by this system is only restricted by signal detection problems due to intrinsic noise in the disparity domain but not by a motoric dead zone.

The various singleness limits (SL) for the three presentation modes (a), (b) and (c) in which interference from vergence eye-movements could be avoided, and which together enclose the presentation mode used to determine the vergence thresholds (VT), are represented in Fig. 3A and C by open circles, solid circles and solid squares respectively; the corresponding doubleness thresholds (DT) in Fig. 3B and D are represented by the same symbols. The singleness limits vary between 2' and 12' [4] and the doubleness thresholds between 6' and 26'.

Inspection of Fig. 3 shows that the upper and lower limits of the diplopia threshold are much larger than the vergence threshold, irrespective of the presentation mode used for determination of the diplopia threshold. This result strongly suggests that vergence eye-movements can be initiated by vertical disparities that are far too small to induce diplopia.

EXPERIMENT 2. THRESHOLDS FOR THE DETECTION OF VERTICAL DISPARITY BY THE SENSORY SYSTEM AND THE SENSORIMOTOR SYSTEM

Introduction

The purpose of this experiment was to compare detection thresholds for the sensorimotor system controlling the initiation of vergence eye-movements in response to vertical disparity with the corresponding detection thresholds for the sensory system controlling the psychophysical assessment of vertical disparity. These thresholds were both determined in a discrimination task which is ideal for this purpose, because the subject is biased to use the sharpest possible criterion for the psychophysical assessments involved. This experiment adds to the information obtained from Experiment 1, since it is known that the sensory system can detect vertical disparity better than the diplopia thresholds indicate. Studies by various authors (Kaufman and Arditi, 1976; Duwaer and Van den Brink, 1981a) show that the criterion 'diplopia', though useful in day-to-day binocular perception, is a lenient criterion for the assessment of disparity information. This makes it interesting to check whether differences remain between the performance of the sensorimotor system and the sensory system when the subject is biased to use the sharpest possible criterion.

Sensory thresholds for the detection of horizontal disparity and vertical monocular separation were also determined. The only purpose of these measurements was to obtain some reference data on the sensory spatial processing capabilities under the particular stimulus conditions used.

Methods

The stimulator. The stimulator is as described for Experiment 1.

Stimuli, psychophysical procedures and calculation of detection thresholds. *(i) Detection thresholds of the sensorimotor system.* For the determination of the detection thresholds of the sensorimotor system controlling vergence eye-movements in response to vertical disparities, the test stimulus with overall vertical disparity shown in Fig. 4A replaced the fixation stimulus of Fig. 2A for 2 sec. The squares used in experiment 1 are reduced to their essentials here, viz. only the horizontal sides with vertical disparity are presented.

The detection thresholds were determined by getting the subject to discriminate between the responses of the nonius lines to test lines with a certain test disparity and to test lines with the disparity that is least effective in initiating vergence eye-movements (i.e. the disparity corresponding to the centre of the region bounded by VT^- and VT^+ as determined in the procedure described in Experiment 1). This task was performed in a temporal 2-alternative forced-choice procedure (interstimulus interval 3 sec) in which the subject was informed about the direction in which the nonius lines might be expected to shift in one of the two presentation intervals in response to the lines with the test disparity in order to optimalize the detection of the shifts induced by the test disparity. The positive and negative disparities (with reference to the reference disparity defined above) giving 50% detection [5] were each determined by linear interpolation from at least 4 detection frequencies

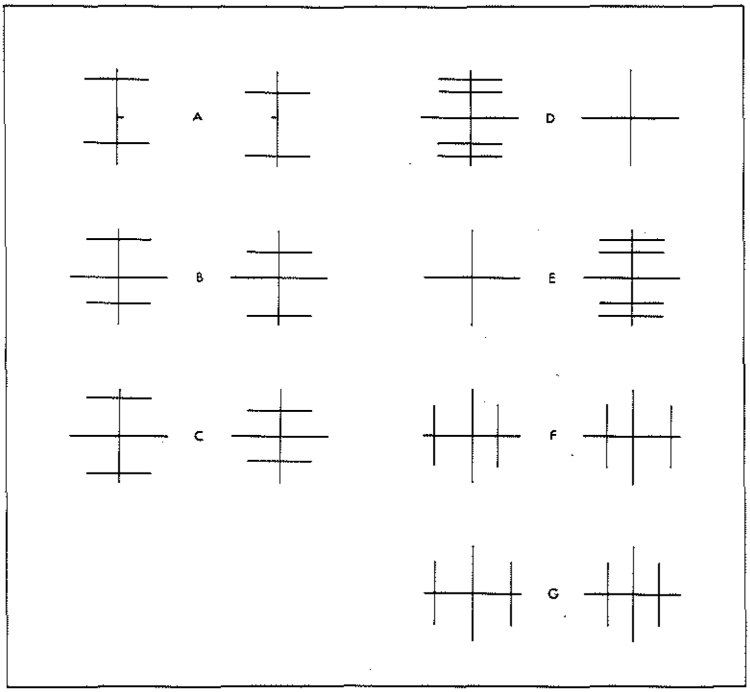

Fig. 4. Schematic representation of the test stimuli used for determination of the thresholds for: initiation of vergence eye-movements (A); detection of vertical disparity (B and C); detection of monocular vertical separation (D and E); detection of horizontal disparity (F and G).

The distance between the two test lines (without disparity or separation) was equal to their length and amounted to 1, 2, 4 or 8°. Stimuli D-G were only used to obtain some reference data serving as measures of the capabilities of sensory processing under the particular experimental conditions used.

between 0.00 and 1.00 that were each determined from 50 trials. The mean result is indicated in Fig. 5A, 5B and 5C by solid triangles. The SE of these thresholds is a factor 10 smaller than the thresholds themselves.

(ii) Sensory thresholds for the detection of vertical disparity. For the determination of the detection thresholds of the sensory system controlling the psychophysical assessment of vertical disparity, the test stimulus with aniseikonic vertical disparity shown in Fig. 4C replaced the fixation stimulus of Fig. 2B for 2 sec. Aniseikonic vertical disparity was used to prevent vergence eye-movements from interfering with the results. In addition the sensory detection thresholds for 160-msec presentation of aniseikonic vertical disparity (see Fig. 4C) were compared with the sensory detection thresholds for 160-msec presentation of the overall vertical disparity (see Fig. 4B) used to determine

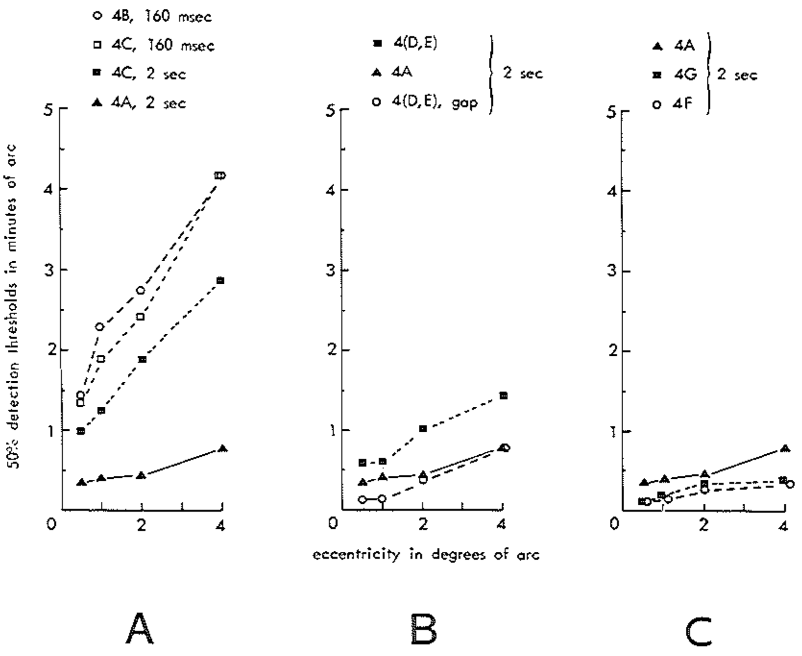

Fig. 5. Detection thresholds (for 50% correct detection) obtained from subject ALD in the temporal 2-alternative forced-choice procedure, plotted as functions of the eccentricity of the lines with disparity or separation. The 50% detection thresholds for the initiation of vergence eye-movements in response to overall vertical disparity (stimulus of Fig. 4A) are indicated in A, B and C by solid triangles.

In A, the solid squares indicate the detection thresholds for 2-sec presentation of aniseikonic vertical disparity (stimulus of Fig. 4C), the open squares the thresholds for 160-msec presentation of aniseikonic vertical disparity (stimulus of Fig. 4C) and the open circles the thresholds for 160-msec presentation of overall vertical disparity (stimulus of Fig. 4B).

In B, the solid squares indicate mean, monocular thresholds for 2-sec presentation of monocular vertical separation (stimuli of Fig. 4D and E), with overlapping lines (2 lines without separation between the midpoints) as reference stimulus and the open circles indicate mean monocular thresholds with adjacent lines (2 lines with a separation equal to the line width) as reference stimulus.

In C, the open circles indicate the thresholds for 2-sec presentation of overall horizontal disparity (stimulus of Fig. 4F) and the solid squares the thresholds for 2-sec presentation of aniseikonic horizontal disparity (stimulus of Fig. 4G).

The data in B and C are presented only to provide some reference data serving as a measure of the capabilities of sensory processing under the particular experimental conditions used.

the detection thresholds of the sensorimotor system, in order to check whether these different types of stimuli yield identical thresholds when vergence eye-movements do not interfere with the results.

The detection thresholds were determined by getting the subject to discriminate between test lines with and without disparity in a temporal 2-alternative forced-choice procedure (interstimulus interval 3 sec). The positive and negative disparities giving 50% detection were each determined by linear interpolation from at least 4 detection frequencies between 0.00 and 1.00 that were each determined from 50 trials. The mean result is indicated in Fig. 5A by solid squares for 2-sec presentation of aniseikonic vertical disparity; by open squares for 160-msec presentation of aniseikonic vertical disparity and by open circles for 160-msec presentation of overall vertical disparity.

(iii) Sensory thresholds for the detection of monocular vertical separation. For the determination of the sensory detection thresholds for monocular vertical separation, the test stimuli shown in Fig. 4D and E replaced the fixation stimulus of Fig. 2B for 2 sec.

The detection thresholds were determined by getting the subject to discriminate between test lines with and without separation in a temporal 2-alternative forced-choice procedure (interstimulus interval 3 sec). The separations giving 50% detection in the left eye (stimulus of Fig. 4D) and in the right eye (stimulus of Fig. 4E) were each determined by linear interpolation from at least 4 detection frequencies between 0.00 and 1.00 that were each determined from 50 trials. The mean result is indicated in Fig. 5B by solid squares.

Detection thresholds were also determined by getting the subject to discriminate between test lines with a separation of 1.2' (equal to line width) and test lines with a larger separation. The mean value of the separations giving 50% detection in the left eye and right eye is indicated in Fig. 5B by open circles.

(iv) Sensory thresholds for the detection of horizontal disparity. For the determination of sensory detection thresholds for horizontal disparity, the test stimuli shown in Fig. 4F and G replaced the fixation stimulus of Fig. 2B for 2 sec.

The detection thresholds were determined by getting the subject to discriminate between test lines with and without horizontal disparity in a temporal 2-alternative forced-choice procedure (interstimulus interval 3 sec). This discrimination was found to be based on the perception of stereoscopic depth differences. The positive and negative horizontal disparities giving 50% detection were each determined by linear interpolation from at least 4 detection frequencies between 0.00 and 1.00 that were each determined from 50 trials. The thresholds obtained for positive and negative horizontal disparities were the same to within the experimental error. They were therefore averaged. This mean result is indicated in Fig. 5C by open circles for overall horizontal disparity (stimulus of Fig. 4F) and by solid squares for aniseikonic horizontal disparity (stimulus of Fig. 4G).

Results and discussion

The data presented in Fig. 5 were obtained from a highly practised subject

(ALD, one of the authors), so one can be reasonably sure that they represent stabilized sensory performance.

The 50% detection thresholds for the sensorimotor system controlling the initiation of vergence eye-movements in response to overall vertical disparity - indicated in Fig. 5A, B and C by solid triangles as a function of the eccentricity of the horizontal lines with vertical disparity - vary between 0.4' and 0.8' and increase with increasing eccentricity.

The corresponding 50% detection thresholds of the sensory system controlling the psychophysical assessment of vertical disparity - indicated in Fig. 5A by solid squares as a function of the eccentricity of the horizontal lines with vertical disparity - were obtained with 2-sec presentation of aniseikonic vertical disparity (stimulus of Fig. 4C). These thresholds (which increase from 1' to 3' with increasing eccentricity) will be equal to the detection thresholds that would have been found without vergence eye-movements for 2-sec presentation of the lines with overall disparity used to determine the detection thresholds for the sensorimotor system. This may be concluded from the observed equality of the 50% detection thresholds obtained with 160-msec presentation of aniseikonic vertical disparity (stimulus of Fig. 4C) and those obtained with 160-msec presentation of overall vertical disparity (stimulus of Fig. 4B), where it is established that vergence eye-movements do not interfere with the results.

The major finding from experiment 2 is that the sensorimotor system controlling vertical vergence eye-movements is apparently more sensitive to vertical disparities than the sensory system controlling the psychophysical assessment of vertical disparity, under the stimulus conditions used (long presentation times and sufficient contour length with disparity).

Some reference values serving as measures of the sensory capabilities of spatial processing under the stimulus conditions used are plotted in Fig. 5B and C. The 50% detection thresholds for 2-sec presentation of monocular horizontal lines with vertical separation (stimuli of Fig. 4D and E) - indicated in Fig. 5B by solid squares - amount to 0.6'-1.6', which is comparable to the values reported by e.g. Jacobs (1979). Comparison of these thresholds with the sensorimotor thresholds - indicated by solid triangles in Fig. 5B - shows that

Table 1. Diplopia thresholds with their SD obtained from subject ALD with 2-sec presentation of the stimulus of Fig. 4C.

Stimulus magnitude (deg arc)	Singleness limit SL ±SD (min arc)	Doubleness threshold DT ±SD (min arc)	Mean of SD of SL and DT (min arc)
1	2.6 ± 0.75	5.8 ± 1.1	0.95
2	3.7 ± 0.8	8.8 ± 1.4	1.1
4	5.2 ± 1.9	11.2 ± 1.8	1.9
8	6.1 ± 3.1	14.0 ± 2.1	2.6

the former are larger. The 50% detection thresholds obtained when the subject is asked to discriminate between monocular lines with a separation of 1.2' (equal to the line width) and monocular lines with larger separations amount to 0.2'-0.8'. These thresholds - indicated in Fig. 5B by open circles - are lower than or equal to the sensorimotor thresholds. The sensory thresholds for the detection of horizontal disparities - indicated in Fig. 5C by open circles for overall horizontal disparity and by solid squares for aniseikonic horizontal disparity - amount to 0.15'-0.4' and are thus lower than all the other spatial detection thresholds mentioned above. Hence, although the sensorimotor thresholds are lower than might be expected given the monocular resolving power, they are not lower than all the sensory thresholds for spatial processing.

GENERAL DISCUSSION

The two major findings which emerge from the experimental results given above are: a) vergence eye-movements can be initiated by vertical disparities that are much too small to induce diplopia; b) the sensorimotor system controlling vertical vergence eye-movements is more sensitive than the sensory system controlling the psychophysical assessment of vertical disparity.

This state of affairs is, of course, quite useful for practical purposes. It means that overall vertical disparities will not be noticed, even when the subject is paying attention to them, because the sensorimotor system continuously eliminates them by reflex actions with a more than sufficient accuracy. It is noteworthy that the accuracy of the sensorimotor system, if stimulated at the *periphery* of the visual field (at least up to 4° eccentricity), would still be sufficient to maintain binocular single vision in the *fovea*.

An important implication of both these findings is that diplopia thresholds should not be interpreted as boundaries of *motoric* 'dead zones' for disparities, i.e. disparity ranges within which a change in disparity does not activate the sensorimotor system. This conclusion reinforces the physiological relevance of the evidence - collected by a signal detection approach by Kaufman and Arditi (1976) and Duwaer and Van den Brink (1981a) - that the diplopia thresholds should not be interpreted as boundaries of *sensory* 'dead zones' for disparities, i.e. disparity ranges within which sensory information about the size of disparity is lost. This was concluded from data showing that cyclic and vertical disparities smaller than the diplopia thresholds can be discriminated reliably. The data obtained in the present study with 2-sec presentation of aniseikonic vertical disparity (stimulus of Fig. 4C) confirm this, since the 50% detection thresholds are much smaller than the corresponding diplopia thresholds (see Table 1).

The lower sensitivity of the sensory system controlling the psychophysical assessment of vertical disparity is unlikely to be simply due to the fact that the subject was not using the sharpest possible criterion. Firstly, because the sensitivities of the sensory system presented above were determined in a subject who was highly practised in sensory detection of vertical disparities. Secondly, because signal-detection considerations provide evidence that the subject was indeed using the sharpest possible criterion: we will now show, that the measured 50% detection thresholds approach the lower limits set by ideal signal detection, given the amount of intrinsic noise in the disparity domain, quite closely.

It follows from signal detection considerations that the lower limit of the 50% detection threshold is set by the intrinsic noise in the disparity domain, according to the expression:

50% detection threshold = 0.955 x SD of intrinsic noise [6].

This relation is represented by the broken line of Fig. 6. The measured 50% detection thresholds at the four eccentricities are plotted with open circles against the mean value of the standard deviations of the corresponding singleness limits and doubleness thresholds as estimate of the standard devia-

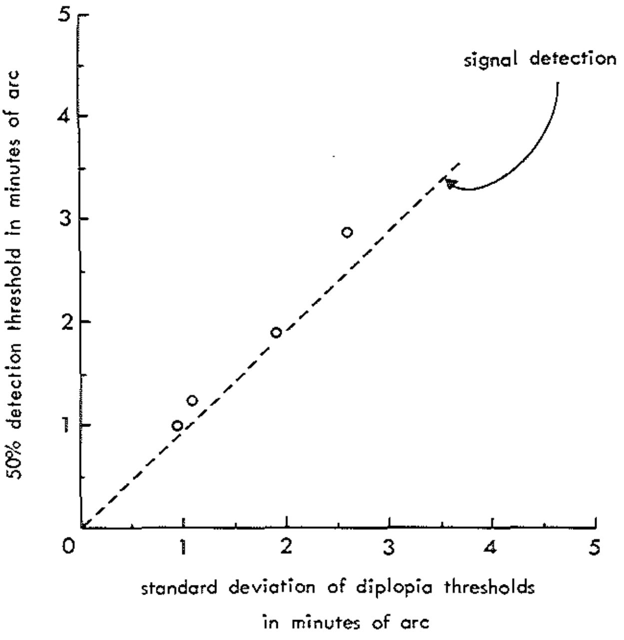

Fig. 6. 50% detection thresholds obtained at 4 eccentricities with 2-sec presentation of the stimulus of Fig. 4C, plotted against the mean of the SD of the corresponding singleness limits and doubleness thresholds. These values are also tabulated in Table 1. The broken line represents the relation between threshold and SD predicted on the basis of signal-detection considerations, assuming no loss of disparity information.

tion of the intrinsic noise. If the measured detection thresholds were a result of pure signal detection they should lie on the broken line; and if not, above it. Inspection of Fig. 6 shows that the 50% detection thresholds do indeed approach the limiting lower level of pure signal detection quite closely [7)]. This would strongly suggest that the subject was using an assessment criterion which was practically as sharp as possible during the determination of sensory detection thresholds for vertical disparity. A second conclusion which is implicit in this analysis is that the detection thresholds obtained can apparently be described without assuming the occurrence of a dead zone!

A *third* major finding is the high sensitivity of the sensorimotor system as such. Up to eccentricities of at least 4°, a vertical disparity as small (in angular measure) as the distance between the centres of neighbouring receptors in the retina is enough to initiate vergence eye-movements (*cf* e.g. Polyak, 1941).

The determination of the sensitivity of the sensorimotor system relied on the subject's ability to detect a change in the alignment of the nonius lines in response to the presentation of the stimulus disparity. This detection is hampered by the continuously changing alignment caused by involuntary eye-movements. It is this difficulty that caused the apparent underestimation of the sensitivity of the sensorimotor system and the lack of dependence on eccentricity of stimulation in Experiment 1 (compare Figs. 3 and 5), where the detection was not optimalized by informing the subject about the direction in which to expect the alignment change 8). We cannot however entirely exclude the possibility that the sensitivity of the sensorimotor system is still being underestimated in Experiment 2.

The sensitivity of the sensorimotor system as estimated in Experiment 2 was found to surpass that of the sensory systems controlling the psychophysical assessment of vertical disparity, and the monocular resolving power. It does not however exceed the sensory capabilities of spatial processing, as evidenced by the still higher sensitivities found for the detection of a gap between two adjacent monocular lines and the detection of relative horizontal disparity using stereoscopic depth as a cue.

The remarkably low thresholds found for the initiation of vergence eye-movements eliminating vertical disparities would imply a remarkably accurate alignment of the eyes in the vertical direction. This has indeed been found to be the case. Vertical disparities occurring spontaneously during continuous observation of e.g. a circular fixation stimulus 1° in diameter remain smaller than 1' of arc (Duwaer and Van den Brink, 1981b).

It is interesting to note that these low thresholds found for the initiation of vergence eye-movements and the resulting accurate alignment of the eyes strongly support the physiological relevance of the concept 'corresponding points' on the retinae of the two eyes.

One important aspect of the sensorimotor system controlling vertical vergence eye-movements, used implicitly in the determination of diplopia thresholds for long presentation times without interference of vergence eye-movements, has not been discussed explicitly yet. We refer to the apparent pooling of disparity information in the visual field preceding the actual initiation of vergence eye-movements.

For instance, 2-sec presentation of horizontal lines above and below the fixation point with vertical disparities of the same sign initiates vertical vergence eye-movements whereas presentation of the same horizontal lines for the same time with vertical disparities of opposite sign does not apparently do so, even when the two lines are separated by as much as 8°. This implies that one can only determine the (absolute) detection thresholds of the sensorimotor system with stimuli that overrule all spurious stimuli in the visual field (such as the boundary of the background field) which might otherwise create 'vergence traps'. It also implies that one can apparently manipulate the stimulus conditions so as to prevent or reinforce the occurrence of vergence eye-movements. Experiments in this direction are now being carried out in an attempt to specify the rules according to which the sensorimotor system pools the disparity information in the visual field.

We wish to conclude with the remark that the ease and accuracy with which vergence eye-movements are initiated in response to vertical disparity may make the determination of the occurrence of vertical vergence eye-movements a useful tool in the assessment of visual performance in the periphery of the visual field. The advantage of this tool is that it does not require the subject to pay attention to the peripheral stimulus: he or she only has to perform a simple foveal task.

ACKNOWLEDGEMENTS

We would like to thank Dr. G.J. van der Wildt, Dr. C.M.M. de Weert and Mrs. A.E.H. Peters for helpful discussions, Mr. C.J. Keemink and Mr. J.B.P. van Deursen for their technical assistance, and the Netherlands Organization for the Advancement of Pure Research (Z.W.O.) for the funds which made this investigation possible.

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NOTES

1. In this paper, all retinal disparities and dimensions of perceived images are expressed in degrees of arc and minutes of arc, which for the sake of simplicity are denoted by e.g. '8^o' or '2'' respectively.

2. The presence of the vertical sides of the squares proved to be irrelevant for the results. They were, however, not removed because their presence facilitates the determination of diplopia thresholds in untrained subjects by reminding them how lines without vertical disparity should look in the periphery of the visual field.

3. The angular dimensions were not corrected for the reduction in size of 2% introduced by the negative spherical correction of -0.75D.

4. Subject AEMR regularly perceived the test stimulus without disparity in diplopia, as can be inferred from comparison of the singleness limit and its SD. This effect, quite often found at the periphery of the visual field (Palmer, 1961; Duwaer and Van den Brink, 1981a), reflects the fact that the percept of a stimulus without disparity at the periphery of the visual field varies between single and double according to foveal standards.

5. The percentage detection is calculated from the percentage identification by correction for the *a priori* detection probability according to the expression:

$$\% \text{ detection} = 2 \times (\% \text{ identification} - 50).$$

6. This expression is derived in the Appendix.

7. It is a conspicuous result that the 50% detection thresholds seem to become smaller than the level 1.49 x SD corresponding to signal detection with the quite likely loss of information about the sign of disparities (Duwaer and Van

den Brink, 1981a). Loss of sign information reflects the fact that disparities of opposite sign produce both doubling (without sign) of the binocular image.

8. Control experiments showed that the apparent underestimation of the sensitivity of the sensorimotor system in Experiment 1 was not due to the presence of the vertical sides of the squares with disparity.

APPENDIX

If the disparity thresholds are determined with reference to criteria chosen out of a continuous scale of possible criteria extending to zero disparity in a disparity domain with constant additive intrinsic noise, then the 50% detection threshold will be determined by signal detection considerations.

If no loss of disparity information may be expected during signal detection, the following relation is obtained:

50% detection threshold

= 0.955 x SD of singleness limit

= 0.955 x SD of doubleness threshold.

These relations may be derived as follows (see also Duwaer and Van den Brink, 1981a).

In the 2-alternative forced-choice procedure, the subject is comparing the percepts of two stimuli presented in succession in order to determine which percept embodies a disparity. In the 3-alternative classification, the subject is comparing the percept of each stimulus presented with reference to two criteria, i.e. two disparity levels.

Assume that: (i) the internal representation of the disparity in the test stimulus is increased with a sample of a normalized Gaussian distribution so that the density function of a large number of internal representations of the same stimulus disparity is:

$$p(d) = \frac{1}{\sigma_d\sqrt{2\pi}} \exp\{\frac{-(d-\delta)^2}{2\sigma_d^2}\},$$

where d = disparity, δ = disparity in the test stimulus, and σ_d = SD of the additive Gaussian noise. (ii) The internal representations of stimuli presented in succession are mutually independent.

Under these assumptions, the statistics of the decisions in the 3-alternative classification procedure are governed by the distribution *p(d)*. This implies that the SD of the disparity thresholds is equal to σ_d.

The frequency of correct discrimination $P_c(\delta)$ in the 2-alternative forced-choice situation, when there is no loss of disparity information, is given by:

$$P_c(\delta) = \int_{-\infty}^{+\infty} p_{sn}(d=x)\, P_n(d<x)\, \partial x$$

where $p_{sn}(d=x)$ = the probability that the internal representation of the stimulus *with* disparity is located at disparity x,

$$p_{sn}(d=x)=\frac{1}{\sigma_d\sqrt{2\pi}}\exp\{\frac{-(x-\delta)^2}{2\sigma_d^2}\}$$

and $P_n(d<x)$ = the probability that the internal representation of the stimulus *without* disparity is located at a disparity that is smaller than x,

$$P_n(d<x)=\int_{-\infty}^{x}\frac{1}{\sigma_d\sqrt{2\pi}}\exp\{\frac{-d^2}{2\sigma_d^2}\}\partial d.$$

The frequency of correct detection will be 50% for $P_c(\delta)=0.75$, which corresponds to $\delta=0.955\sigma_d$.

IV

BINOCULAR SINGLE VISION UNDER HIGHLY DEMANDING CONDITIONS

Chapter IV deals with binocular single vision under highly demanding conditions.
When the present thesis was nearly finished, several studies were published claiming a quite surprising reduction of the accuracy of (motor) ocular alignment on a visual stimulus and a rise in the sensory tolerance to retinal disparities by up to one order of magnitude under two highly demanding conditions, viz. binocular fixation during active head rotation and forced vertical divergence of the eyes.
These experiments were replicated in two studies using a specially designed afterimage method to measure ocular alignment instead of the 'objective' method used in the above-mentioned studies which is based on the use of special suction-type contact lenses on the eyes.

4.1 ASSESSMENT OF RETINAL IMAGE DISPLACEMENT DURING HEAD MOVEMENT USING AN AFTERIMAGE METHOD

A.L. Duwaer*

ABSTRACT

An easily practicable afterimage method is presented which can be used to study the accuracy of binocular fixation in observers who are free to move their head during the performance of their visual task.

This afterimage method has been used to measure retinal image displacement during binocular fixation with active head rotation about a vertical axis. The results confirm previously published reports that fixation accuracy in the horizontal direction deteriorates as a result of a head rotation. However, both retinal image displacements and fixation disparities were found to remain much smaller (by a factor of 3 and 8 respectively) than the values previously reported in the literature for similar head rotations (peak-to-peak amplitude: 20°, frequency: 0.66 Hz). Moreover, our results show that fixation accuracy fell not only in the horizontal direction, but also in the vertical direction by about the same factor.

It is concluded that eye-movement compensation of active head rotation may be much better than previously reported in the literature, and good enough to prevent deterioration of vision. The deterioration of fixation accuracy during active head rotation does not seem to be completely due to limitation of oculomotor performance; some non-specific effects such as the increased difficulty of the (consciously performed) fixation task may also play a role.

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INTRODUCTION

A technically impressive recording technique based on the use of a magnetic field and search coils in contact annuli held on to the eyes by suction, permitting measurements in which the subject is free to move the head without causing artefacts in the recording, has recently become operational (Hartman and Klinke, 1976; Collewijn, 1977). This new technique has triggered the study of a new topic in eye-movement research, viz. the characteristics of retinal image motion with a freely moving head (Skavenski et al. 1979; Steinman and Collewijn, 1980; Steinman et al., 1981). Unfortunately, the applicability of the method is limited by the expense of the equipment involved and the complexity of the measuring techniques.

These considerations encouraged us to present a much simpler method based on a suitable afterimage technique which does not make use of expensive, complicated equipment and is much more convenient for the test subject, who no longer has to have special suction-type contact annuli mounted on the eyes. This new method permits the simultaneous determination of horizontal and vertical retinal image displacements, and provides direct estimates of retinal image displacement without the need of applying various complicated corrections for a) the magnification factor introduced by spectacles (*cf*. Ogle, 1971), b) angular rotation of the eye compensating for the translation of the eye caused by head rotation, and c) underestimation of image displacements (of objects closer than optical infinity) caused by the fact that the principle nodal point of the optics of the eye lies anterior to the centre of rotation of the eye, so that the angle of image rotation will be greater than the rotation of the eye relative to the target (Steinman et al., 1981).

The afterimage method has been used to assess horizontal and vertical retinal image displacements during active head rotation about a vertical axis, in order to test the claims of Steinman and Collewijn (1980) and Steinman et al. (1981) that eye-movement compensation of active head rotation is far from perfect and that binocular vision remains single in spite of the occurrence of horizontal fixation disparities of up to 3° 1) which exceeds by far the largest diplopia thresholds reported for similar stimuli (Mitchell, 1966; Duwaer and Van den Brink, 1981a).

METHODS

Stimuli

Retinal image displacements were determined for active head rotation with a frequency of 0.66 Hz and a peak-to-peak amplitude of 20° during binocular fixation of a target at a distance of 2 m. This target, which is schematically illustrated in Fig. 1B, consisted of a yellow light-emitting diode (LED) with a diameter of 3' at the centre of a cross consisting of a vertical and a horizontal black line (width 2', length 1.4°) on a white background (dimensions 1.4° x 1.4°, luminance level 25 cd/m^2). The target was surrounded by dimly illuminated white cardboard. The frequency of active head rotation of 0.66 Hz was chosen because the study of Steinman et al. (1981) provides data at this frequency, and because our own preliminary observation showed that vision started to deteriorate at higher frequencies. The retinal image displacements observed were compared with those determined during steady fixation with the head supported by a chin-rest. The subject was asked to concentrate all his attention on keeping his eyes on the centre of the target as well as possible.

The tempo for the active head rotation was indicated by turning the LED off for short periods (t_{off} = 30 msec) between the 720 msec 'on' periods. The subject was asked to change the direction of head rotation at each 'off' pulse. The peak-to-peak amplitude of head rotation was monitored by following the excursion of the collimated light beam from a flashlight attached to the frame of an earphone set worn by the subject. The subjects were allowed ample opportunity to practice moving their head smoothly with the desired amplitude and frequency.

Afterimage method for the assessment of retinal image displacement

The afterimage method used to determine retinal image displacement is based on the well-known facts that a) an afterimage provides a retinal 'landmark', so that the displacement of an observed scene with respect to an afterimage directly reflects retinal image displacement (see e.g. Ditchburn, 1973) and b) while an afterimage may fade within a few seconds when seen against a background field of constant luminance, it can be viewed for much longer against a temporally modulated background field (see e.g. Magnussen and Torjussen, 1974); in fact, the fluctuating background even *regenerates* an afterimage that has faded to invisibility when seen against a constant background.

The *first* series of experiments ran as follows:

(i) The subject started by rotating his head to and fro about a vertical axis as described above, while keeping his eyes carefully fixed on the LED in the middle of the white background. An afterimage was imprinted on the retinae at a randomly chosen phase of the head rotation by actuating a photographic

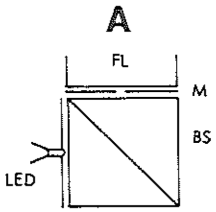

Fig. 1A. Schematic representation of the stimulus configuration. A circular hole (diameter 6') in a mask (M) was given the same perceived location as a light-emitting diode (LED, diameter 3') with the aid of a beam splitter (BS). By actuating the photographic flash (FL) an afterimage could be imprinted on the retinae of the circular hole at the LED-location.

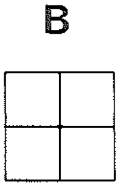

Fig. 1B. Schematic representation of the frontal view of the fixation target. The fixation target consisted of a yellow LED (diameter 3') at the centre of a cross consisting of a vertical and horizontal black line (width 2', length 1.4°) on a white background (dimensions 1.4° x 1.4°; mean luminance level 25 cd/m^2).

flash (duration 20 msec) behind a mask with a circular hole (diameter 6') which had been given the same perceived location as the fixated LED with the aid of a beam splitter (*cf*. Fig. 1A). The subject then looked at a TV screen (dimensions 7.4° x 4.9°; mean luminance level 19 cd/m^2; situated 5° below the fixation target), the luminance of which was sinusoidally modulated with a frequency of 2.7 Hz and a depth of 100%; the occurrence of an afterimage in the left eye with the right eye closed, and vice versa, was checked under these conditions. The fact that closing one of the eyes causes the afterimage in this eye to disappear so that the afterimage in the other (open) eye can be perceived without interference was verified by the use of different afterimages for the two eyes, e.g. a vertical and horizontal line or dots at different locations (*cf*. third series of experiments described below). Afterimages were always found to occur in both eyes (unless extinguished by closing one eye, as indicated above). It should be stressed that when the eye is opened again, the afterimage reappears (until it has faded with passage of time).

(ii) The subject subsequently looked at the white background (of constant luminance level 25 cd/m^2) around the LED for 5-7 seconds until the afterimages were no longer visible. It may be mentioned for the sake of clarity that it is one of the essential features of this method that though the afterimages are no longer visible under these conditions, they are still latently present, and can be regenerated by looking at a background field of fluctuating luminance; of course, even with a fluctuating background the afterimages do fade gradually and will disappear completely in a matter of a minute or two. The afterimages are allowed to fade to invisibility at this stage of the experiment in order to prevent interference with the next fixation task, as visible afterimages provide the subject with information about retinal image displacements and the preceding fixation position which could be used to control the fixation position. The subject then lowered his chin several centimeters to put his head on a chin rest and tried to fixate the LED as well as possible, the position of the LED again being imprinted on the two retinae by actuating the photographic flash.

(iii) The subject then quickly shifted his gaze downwards (with his chin still on the chin rest) to the TV screen with its temporally modulated luminance. These viewing conditions regenerated the first afterimage, so that the subject could now see *two* afterimages in each eye, the second one being appreciably larger and brighter than the first for about 10 - 20 seconds. The subject now closed the left eye for a moment and memorized which of the two afterimages in the right eye was produced second (being still bigger and brighter). He then did the same for the afterimages in the left eye, by closing the right eye. The x and y coordinates of the centre of the *first* afterimage were then estimated with reference to the location of the centre of the second afterimage using the scale provided by horizontal and vertical scale units of 15' depicted on the TV screen. This was done for the left eye by closing the right eye and for the right eye by closing the left eye. The subject plotted the coordinates thus observed on graph paper. He was advised to increase the accuracy of the estimation by taking his time and by looking at the afterimages in the left eye and those in the right eye alternately. The diameter of the afterimage amounted to about 0.3 scale unit (about 5') during the time that the coordinates were estimated. The time available for the estimation was about 1 minute, which proved to be more than sufficient after a short training period. As soon as the afterimages were not visible anymore while looking at the temporally modulating luminance of the TV-screen, the subject repeated the sequence (i), (ii) and (iii) a total of 25 times.

A *second* series of 25 determinations as described above was performed but now without active head rotation in (i). Both the first and the second afterimages were formed in this series with steady fixation of the head on a chin rest. Apart from this, the experimental conditions were identical with those described above.

Finally, a *third* series of experiments was carried out in which the two afterimages in each eye were formed not by successive flashes through a mask with one hole, but simultaneously using masks with two holes with known physical coordinates. The subject was told which of the two afterimages should be used as a reference for estimation of the coordinates. The physical x and y coordinates of the other hole varied between 0 and 1.5 scale units with x and y discrepancies between the coordinates presented to the two eyes of up to 0.6 scale unit.

It took the subjects 1 - 1.5 hours to do one series of experiments, several rest periods included. The first two series were performed on the same day, the third series on another day.

Data analysis

A coordinate obtained in the *first* series (with active head rotation) represents the difference between a sample of the distribution of retinal image locations during active head rotation with variance $\sigma^2_{0.66}$ and a sample of the distribution of retinal image locations without head movements with variance σ^2_0, plus a sample of a distribution (of variance σ^2_{ce}) reflecting the limited accuracy of the estimated coordinates as such without interference from eye-movements. Because of the large time interval between successive samples of the distributions of retinal image locations and the completely different cause of the limited accuracy of estimated coordinates as such, the samples will be statistically independent. Consequently, the coordinates will yield a distribution of variance:

$$\sigma_{II}^2 = \sigma_{0.66}^2 + \sigma_0^2 + \sigma_{ce}^2 \tag{1}$$

A coordinate in the *second* series (with no head rotation at all) represents the difference between two statistically independent samples of the distribution of retinal image location without head movements, plus a sample of the distribution reflecting the limited accuracy of the estimated coordinates as such. These coordinates, therefore, yield a distribution of variance:

$$\sigma_I^2 = \sigma_0^2 + \sigma_0^2 + \sigma_{ce}^2 = 2\sigma_0^2 + \sigma_{ce}^2 \tag{2}$$

A coordinate obtained in the *third* series represents the estimated coordinate (c_e) given the functional relation with the physical coordinate (c_{ph}), plus a sample of the distribution reflecting the limited accuracy of the estimated coordinates as such. The functional relation was chosen as:

$$c_e = \frac{1}{\alpha} c_{ph} \tag{3}$$

The constant α was introduced to account for any systematic deviations from the expected relation $c_e = c_{ph}$. The variance σ_{ce}^2 of the distribution reflecting the limited accuracy of the estimated coordinates as such will then be

$$\sigma_{ce}^2 = \mathrm{var}\ (c_e\big|_{c_{ph}} - c_{ph}/\alpha) \tag{4}$$

where $c_e\big|_{c_{ph}}$ represents the estimated coordinate given c_{ph}.

It follows from (1), (2) and (4) that [2]

$$\sigma_{0.66} = \sqrt{\sigma_{II}^2 - \tfrac{1}{2}\{\sigma_I^2 + \mathrm{var}(c_e\big|_{c_{ph}} - c_{ph}/\alpha)\}} \text{ scale units} \tag{5}$$

$$\sigma_0 = \sqrt{\tfrac{1}{2}\{\sigma_I^2 - \mathrm{var}(c_e\big|_{c_{ph}} - c_{ph}/\alpha)\}} \qquad \text{scale units} \qquad (6)$$

Using equation (3) and the fact that a physical scale unit amounts to 15' it follows that

$$\sigma_{0.66} = 15\alpha\sqrt{\sigma_{II}^2 - \tfrac{1}{2}\{\sigma_I^2 + \mathrm{var}(c_e\big|_{c_{ph}} - c_{ph}/\alpha)\}} \quad \text{minutes of arc} \qquad (7)$$

$$\sigma_0 = 15\alpha\sqrt{\tfrac{1}{2}\{\sigma_I^2 - \mathrm{var}(c_e\big|_{c_{ph}} - c_{ph}/\alpha)\}} \qquad \text{minutes of arc} \qquad (8)$$

So, by calculating the standard deviations of the distribution of coordinates in the first series with active head rotation (σ_{II}) and in the second series without active head rotation (σ_I), and by calculating the standard deviation (σ_{ce}) of the distribution reflecting the limited accuracy of estimated coordinates as such and α (= c_{ph}/c_e), we can obtain a measure of the standard deviation of the distribution of retinal image locations during active head rotation ($\sigma_{0.66}$) and during absence of head movement (σ_0). This has been done separately for the x and y coordinates of the afterimage in the left eye (x_L and y_L) and for those of the right eye (x_R and y_R). In addition, the standard deviations of the distribution of horizontal and vertical fixation disparities were calculated. This calculation was based on the standard deviations of the distribution of discrepancies ($x_L - x_R$) and ($y_L - y_R$) between the coordinates in the left eye and those in the right eye.

Subjects

The data were obtained from 5 subjects who all had normal stereopsis (stereoacuities better than 1 according to the random-dot TNO test distributed by Laméris, Utrecht, The Netherlands), and (Landolt-C) visual acuities better than 1 in either eye. The subjects were emmetropic except for subject ALD who was corrected for myopia with -0.75 dioptres for both eyes.

RESULTS AND DISCUSSION

Examples of the distributions of the coordinates for the left eye (L) and for the right eye (R) and of the distribution of the discrepancies (L-R) between the coordinates for the left and right eyes are given in Figs. 2 and 3. These

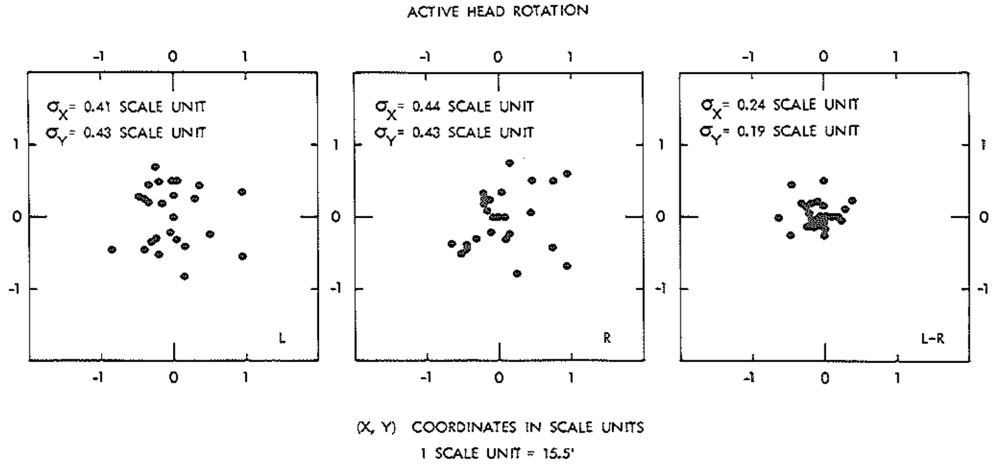

Fig. 2. (X,Y) coordinates of an afterimage imprinted during active head rotations, with respect to a reference afterimage imprinted subsequently during steady fixation without head movement. Both afterimages represent the same point in the visual field, so that both x and y coordinates should ideally be zero if visual performance were perfect. The coordinates are expressed in (calibrated) scale units corresponding to 15.5'. The data (comprising 25 pairs of afterimages) were obtained from subject GvA, and are presented for the left eye (L) and the right eye (R) separately. The third graph indicated by "L-R" represents the discrepancies between the coordinates for the two eyes. The peak-to-peak amplitude of the active head rotation amounted to 20° and the rotation frequency to 0.66 Hz. The standard deviations (σ_x and σ_y) given are used to calculate the standard deviations of the underlying distributions of retinal image locations during active head rotation and in the absence of head movement.

distributions were obtained from one of the subjects in the first series with active head rotation (Fig. 2) and in the second series without head movements (Fig. 3). The estimated x and y coordinates obtained from the same subject in the third series are plotted in Fig. 4 as a function of the corresponding physical coordinates. The broken line in Fig. 4 was obtained by fitting the relation 'estimated coordinate = $1/\alpha$ x physical coordinate' by linear regression to the experimental points together with their reflections in the origin; this stratagem ensures that the regression line passes directly through the origin.

It should be noted that if both eyes of this subject had remained perfectly

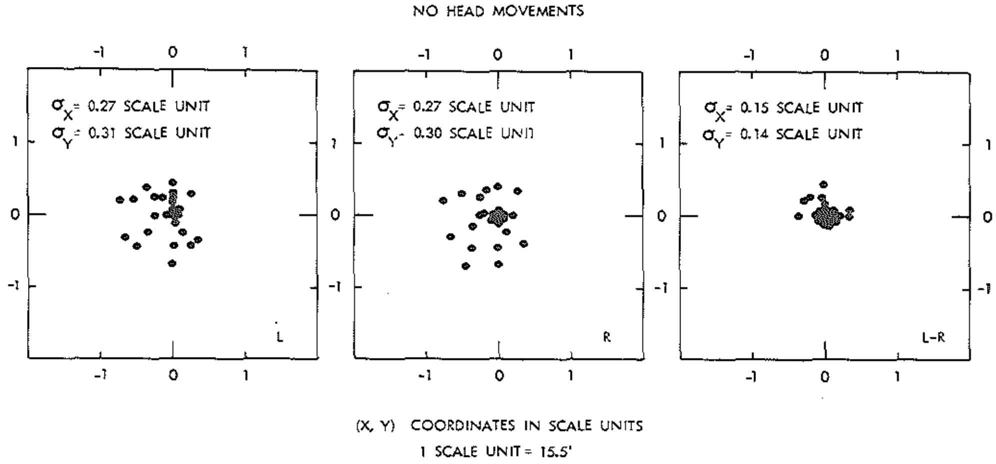

Fig. 3. (X,Y) coordinates of an afterimage imprinted without head movement, with respect to a reference afterimage imprinted under the same conditions (for further details, see legend to Fig. 1).

aligned with respect to the fixation target, and if the estimated coordinates had been equal to the physical coordinates, all points in Figs. 2 and 3 would have fallen at the origin (0,0) and all points in Fig. 4 would lie on the line $c_e = c_{ph}$.

The fixation accuracy has been quantified by calculating the standard deviations of the underlying distributions of retinal image locations without head movement (σ_0) and with active head rotation ($\sigma_{0.66}$), using equations (7) and (8). The standard deviations σ_{II} were calculated from the distributions shown in Fig. 2, σ_I from the distributions shown in Fig. 3 and both σ_{ce} and the factor c_{ph}/c_e from the experimental points of Fig. 4. The results of this calculation are given in Table 1, together with the values calculated for the 4 other subjects tested.

Before discussing the calculated standard deviations of the distributions of retinal image locations in the two fixation tasks, we would like to draw the reader's attention to one surprising and one disappointing result. The surprising result is that the physical coordinates tend to be overestimated ($\alpha \lesssim 1$). This might point to a tendency to project the afterimages on a plane slightly

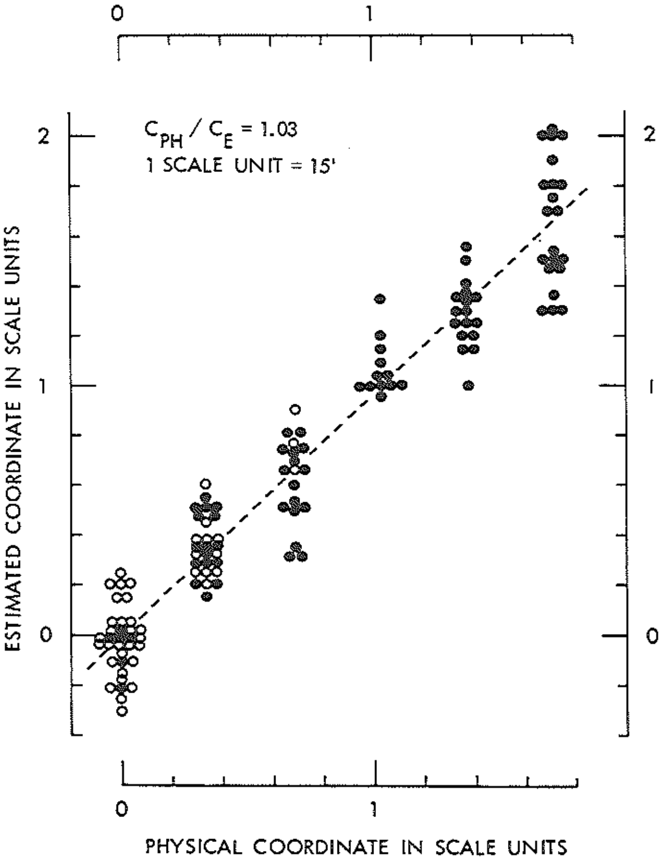

Fig. 4. X and Y coordinates (in scale units = 15') of an afterimage imprinted without head movement with respect to a reference afterimage (both afterimages being formed at the same time, with the aid of masks with two holes), plotted as a function of the known physical coordinates of one hole in the mask with respect to the other. The dots represent the X and Y coordinates for 22 pairs of afterimages in the left eye and 22 pairs in the right eye, while the open circles represent the discrepancies between the coordinates for the left and right eyes. The data obtained in the X direction did not differ from those in the Y direction. The broken line was obtained by fitting by linear regression the relation 'estimated coordinate = $\frac{1}{\alpha}$x physical coordinate' to the experimental points and the mirror images of these points in the third quadrant (the points (-x, -y)); this stratagem ensures that the regression line passes through the origin.

Table 1. The ratio c_{ph}/c_e and various standard deviations in scale units and in minutes of arc for the horizontal and vertical directions.

Horizontal

Subject	$\sigma_{ce}\|_{L,R}$ (s.u.)	$\sigma_{ce}\|_{L-R}$ (s.u.)	c_{ph}/c_e	$\sigma_{I}\|_{L}$ (s.u.)	$\sigma_{II}\|_{L}$ (s.u.)	$\sigma_{I}\|_{R}$ (s.u.)	$\sigma_{II}\|_{R}$ (s.u.)	$\sigma_{I}\|_{L-R}$ (s.u.)	$\sigma_{II}\|_{L-R}$ (s.u.)
ALD	0.15	0.09	1.05	0.29	0.81	0.31	0.66	0.17	0.43
GvA	0.17	0.14	1.03	0.27	0.41	0.27	0.44	0.15	0.24
PV	0.26/ 0.15	0.20/ 0.15	0.81	0.20	0.68	0.21	0.79	<0.15	0.25
JAR	0.20	0.10	0.92	0.63	0.99	0.66	0.98	0.16	0.32
HGG	0.20	0.17	0.89	0.42	0.56	0.40	0.65	0.15	0.24

Vertical

Subject	$\sigma_{ce}\|_{L,R}$ (s.u.)	$\sigma_{ce}\|_{L-R}$ (s.u.)	c_{ph}/c_e	$\sigma_{I}\|_{L}$ (s.u.)	$\sigma_{II}\|_{L}$ (s.u.)	$\sigma_{I}\|_{R}$ (s.u.)	$\sigma_{II}\|_{R}$ (s.u.)	$\sigma_{I}\|_{L-R}$ (s.u.)	$\sigma_{II}\|_{L-R}$ (s.u.)
ALD	0.15	0.09	1.05	0.15	0.32	0.16	0.30	0.05	0.07
GvA	0.17	0.14	1.03	0.31	0.43	0.30	0.43	0.14	0.19
PV 3)	0.26/ 0.15	0.20/ 0.15	0.81	0.25	0.56	0.26	0.53	<0.15	0.23
JAR	0.20	0.10	0.92	0.52	1.08	0.52	1.06	0.04	0.16
HGG	0.20	0.17	0.89	0.38	0.48	0.43	0.55	0.11	0.19

Horizontal

Subject	$\sigma_{o}\|_{L}$ (min)	$\sigma_{o}\|_{R}$ (min)	$\sigma_{o}\|_{L-R}$ (min)	$\sigma_{0.66}\|_{L}$ (min)	$\sigma_{0.66}\|_{R}$ (min)	$\sigma_{0.66}\|_{L-R}$ (min)
ALD	2.8	3.0	1.6	12.3	9.7	6.4
GvA	2.3	2.3	<2.3	5.3	5.8	3.0
PV	1.1	1.3	<1.8	7.6	9.1	2.4
JAR	5.8	6.1	1.3	12.0	11.7	4.0
HGG	3.6	3.3	<2.2	6.1	7.6	2.4

Vertical

Subject	$\sigma_{o}\|_{L}$ (min)	$\sigma_{o}\|_{R}$ (min)	$\sigma_{o}\|_{L-R}$ (min)	$\sigma_{0.66}\|_{L}$ (min)	$\sigma_{0.66}\|_{R}$ (min)	$\sigma_{0.66}\|_{L-R}$ (min)
ALD	<1.8	0.6	<1.1	4.5	4.0	<1.3
GvA	2.9	2.8	<2.1	5.4	5.5	1.9
PV 3)	1.7	1.8	<1.8	5.8	5.4	2.2
JAR	4.7	4.7	<0.9	13.8	13.5	1.9
HGG	3.1	3.6	<1.7	4.9	5.8	1.7

s.u. = scale unit = 15 x c_{ph}/c_e minutes of arc

The significance of the various symbols in the column headings is explained in the text.

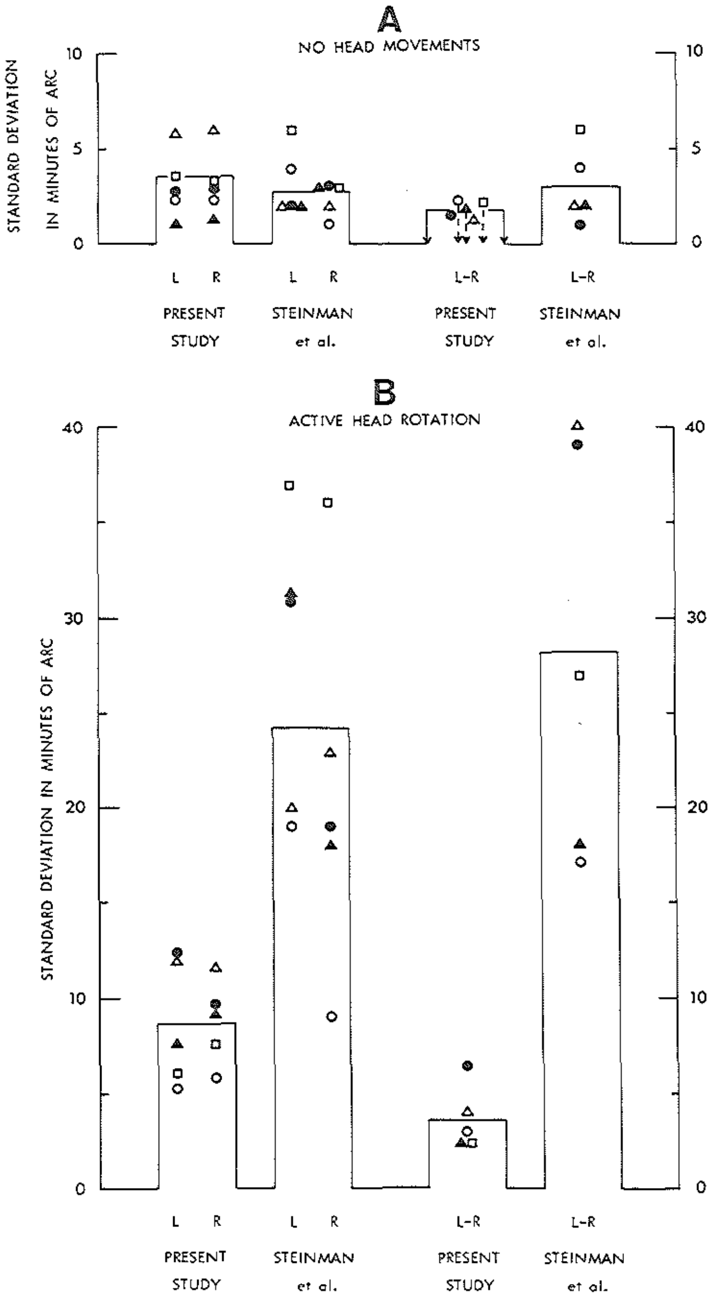

Fig. 5. Standard deviations (in minutes of arc) of the retinal image locations (L and R) in the horizontal direction and of the horizontal fixation disparities (L-R) obtained in the present study and by Steinman et al. (1981; values taken from Table 1). Fig. 5A displays the standard deviations when the subjects did not move their head and Fig. 5B those for active head rotation

of the head. The different symbols represent the data obtained from the different subjects. The height of the vertical bars indicates the arithmetic mean of the standard deviations.

behind that of the TV screen. It should, however, be borne in mind that the subjects had not received any feedback on their performance in this task of estimating the coordinate from afterimages of finite width at an eccentric retinal location. The disappointing result is that the fixation accuracy without head movements may exceed the accuracy of estimating the coordinates, so that estimation of this fixation accuracy may become comparatively inaccurate.

In order to facilitate comparison of the fixation accuracies in the horizontal direction found in this study with those reported by Steinman et al. (1981), the results of both studies are plotted in Fig. 5.

It may be noted firstly that there is fairly good agreement between the standard deviations of the retinal image locations without head movement obtained by the afterimage method and by the objective method (see Fig. 5A); of course, these experimental conditions place least demands on both the subject and the objective method of measurement.

Secondly, we find that the afterimage data on the distributions of fixation disparities without head movement confirm the data obtained with dichoptic nonius markers and a psychophysical procedure by Duwaer and Van den Brink (1981b), suggesting high alignment accuracy of the eyes.

Inspection of Fig. 5B shows that the data obtained by the afterimage method agree with those obtained by Steinman and Collewijn (1980) and Steinman et al. (1981) in demonstrating a drop in the accuracy of fixation during active head rotation.

However, there is less agreement concerning the extent to which the fixation accuracy falls. It can be seen from Fig. 5B that during active head rotation the mean standard deviations found for the distribution of retinal image locations in the horizontal direction and for the distribution of horizontal fixation disparities amount to 8.7' and 3.6' respectively in the present study, but were much higher (24' and 28' respectively) according to Steinman et al. (1981). Our results thus imply that eye-movement compensation of active head rotation may be much better than Steinman's data indicate, provided the subject concentrates on keeping his eyes on a well defined fixation stimulus and is not distracted nor hindered by the presence of suction-type contact annuli on his eyes. This conclusion agrees with a similar one drawn by Sheedy (1981), who also studied the stability of fixation with and without head movements by a psychophysical procedure.

The afterimage method also provided data on vertical fixation accuracy; Steinman and co-workers did not give comparable data concerning this point. Inspection of Table 1 shows that the deterioration of the vertical fixation accuracy hardly differs from that of the horizontal fixation accuracy. This is a remarkably finding since active head rotation about a vertical axis requires large corrective horizontal eye-movements but little or no corrective vertical eye-movement. The deterioration of vertical fixation accuracy may, therefore, indicate a substantial amount of cross-talk between the horizontal and vertical directions, which would represent a serious limitation on oculomotor performance. However, an alternative explanation is that the loss of horizontal fixation accuracy during active head rotation is not due to limitations on the ability of the motor system to use and coordinate visual and vestibular signals, but to the subject's unfamiliarity with the consciously controlled fixation task, which may be expected to lower their performance in both the horizontal and vertical directions.

Both Steinman and Collewijn (1980) and Steinman et al. (1981) compared their data on horizontal retinal image displacements with visual performance data in order to account for the test subjects' subjective observation that vision remained fused, stable and clear during active head rotation. They concluded that it is necessary to assume that signals generated in the oculomotor system activate special neuronal processes to prevent deterioration of visual perception during active head rotation, as the accuracy of the induced eye-movement compensations was found not to be sufficient for this purpose.

The data obtained in the present study permit a similar comparison and moreover have the advantage over the findings of the above-mentioned authors that both eye-movement data and visual perception data were obtained using similar stimuli without contact annuli held on the eye by suction.

It can be calculated from the standard deviations for active head rotation that the retinae were stimulated 95% of the time at horizontal eccentricities of less than 11' - 25' (= 1.96 $\sigma_{0.66}|_{L,R}$), with horizontal disparities of less than 5' - 13' (= 1.96 $\sigma_{0.66}|_{L-R}$) and with horizontal velocities of less than (0.7 - 1.7)°/sec. The velocities were estimated by assuming that the retinal image moves sinusoidally across the retina with the same frequency ($\nu = 0.66$ Hz) as the head rotation and with the above-mentioned amplitude A of 11' - 25', so that the velocity of retinal image movement is a cosine function ($\frac{d}{dt}(A\sin 2\pi\nu t) = 2\pi\nu A\cos 2\pi\nu t$) the maximum value of which equals $2\pi\nu A =$ (0.7 - 1.7)°/sec 4). Higher velocities, eccentricities and fixation disparities than the above-mentioned values can be disregarded because they will occur for so short a time that their role in visual perception will be negligible.

Now previous studies have shown that visual acuity is hardly lowered at eccentricities of 11' - 25' (see e.g. Jacobs, 1979), that foveal diplopia thresholds for horizontal disparities in dots and line usually amounts to at least 10' (Mitchell, 1966; Duwaer and Van den Brink, 1981a) and that retinal velocities lower than 1.5°/sec do not lead to deterioration of contrast perception (Ditchburn, Fender and Mayne, 1959; Sharpe, 1972; Drysdale, 1975; Westheimer and McKee, 1975; King-Smith and Riggs, 1978; Murphy, 1978). In view of these findings it is not at all surprising that our subjects reported that vision remained fused, stable and clear during active head rotation 5). Our data indicate that the accuracy of eye-movement compensation of active head rotation alone is sufficient to prevent deterioration of visual perception, and hence that there is no need to assume that signals generated in the oculomotor system activate special neuronal processes to this end.

It may be asked why our conclusions differ so fundamentally from those of Steinman and Collewijn (1980) and Steinman et al. (1981) on this point. In our opinion, the most likely explanation is the unnatural conditions under which their test subjects had to work. As suggested several times during the course of this article, the presence of suction-type contact annuli on the eyes is likely to interfere considerably with visual performance when the experimental test conditions place high demands. Our afterimage method places no such unnatural load on the subjects, and our results indicate that it does not introduce any extra experimental errors.

ACKNOWLEDGEMENTS

I would like to thank Prof. Dr. H. Collewijn, Dr. M. Rodenburg, Prof. Dr. G. van den Brink and Mrs. A.E.H. Peters for helpful discussions, Dr. R.H. Bathgate for improving the English and the Netherlands Organization for the Advancement of Pure Research (Z.W.O.) for the funds which made this investigation possible.

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NOTES

1. In this paper, all angular dimensions will be expressed in degrees ($^{\circ}$) and minutes (') without the qualification 'of arc' each time.

2. If the measured values of σ_I^2 becomes so small that

$$\sigma_I^2 \overset{<}{\cong} \mathrm{var}\,\{c_e\big|_{c_{ph}} - \frac{c_{ph}}{\alpha}\},$$

σ_I^2 will assumed to be a second estimate of σ_{ce}^2 so that σ_0^2 can be neglected. Formula (5) can then be read as

$$\sigma_{0.66} = \sqrt{\sigma_{II}^2 - \bar{\sigma}_{ce}^2},$$

where $\bar{\sigma}_{ce}^2$ is the mean value of two estimates of σ_{ce}^2, viz. σ_I^2 and

$$\mathrm{var}\,\{c_e\big|_{c_{ph}} - \frac{c_{ph}}{\alpha}\}.$$

The value of σ_0 will then be denoted by $\sigma_0 < \bar{\sigma}_{ce}$ in Table 1.

3. When subject PV did not move his head, 60% of the pairs of afterimages fully overlapped. Due to this overlapping σ_{ce} for this fixation task was found to be smaller than for the other fixation task with active head rotation, and only an upper limit could be given for $\sigma_I\big|_{L-R}$. The values of σ_0 and $\sigma_{0.66}$ were calculated using equation (2) with the smaller value of σ_{ce}, and equation (1) with the larger value of σ_{ce} and the previously calculated value of σ_0.

4. The recordings of retinal image displacements during active head rotation presented by Steinman and Collewijn (1980) and Steinman et al. (1981) show that the retinal image moves on the average sinusoidally across the retina.

5. Subject ALD, who has had a great deal of practice in diplopia investigations, reported seeing the fixation target double regularly during active head rotation.

4.2 A SECOND LOOK AT THE NONMOTOR COMPONENT OF THE FUSIONAL RESPONSE TO VERTICAL DISPARITY USING AN AFTERIMAGE METHOD

A.L. Duwaer*

ABSTRACT

An afterimage method has been used to investigate the relative magnitudes of the nonmotor and motor components of the fusional response to vertical disparity in a complex visual stimulus of diameter 57° consisting of 50 horizontal lines and a square of side 2.5° in the middle.

The amplitude of the fusional response was found to be in the range 3° - 6° of which the nonmotor component only amounted to 8' - 15', i.e. 2% - 10% of the total. When the 50 horizontal lines were omitted from the stimulus so that only the central square of side 2.5° remained, the fusional amplitudes only decreased by 25% while the absolute level of the nonmotor components remained the same.

The nonmotor components found here are much smaller than those (amounting to about 2° or 25% - 40% of the total response) recently reported in the literature. Various possible explanations for this difference are discussed.

INTRODUCTION

In a recent article, Kertesz (1981) presented the results of objective measurements of the effect of stimulus size on fusional response and the relative mag-

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nitudes of the nonmotor and motor components of this response. His three major findings were: 1) the fusional response to a vertical disparity may increase up to 6° with increasing stimulus size, 2) during this increase, the relative proportions of the motor (vergence) and nonmotor components remain roughly constant, and 3) the nonmotor component typically amounts to 25% - 40%, irrespective of the stimulus size.

At first sight, these results would appear to be in agreement with the earlier findings of e.g. Ellerbrock (1949) and Ogle and Prangen (1953). Ellerbrock showed that the fusional response to vertical disparity in black disks may increase up to more than 4° as the size of the disk is increased. Ogle and Prangen - who used dichoptic nonius markers to determine the relative magnitudes of the motor and nonmotor components of the fusional response - showed that the nonmotor component increases (typically in a linear fashion) with the vertical disparity of the stimulus.

However, if we compare Kertesz's results with those of the other authors in greater detail, appreciable discrepancies appear. Kertesz (1981) stressed the importance of using a complex stimulus with as many as 50 horizontal lines and a diameter of 57° to reach fusional responses of 3° - 6°, while Ellerbrock (1949) only needed simple black disks subtending an angle of 2° to obtain similar fusional responses. The typical nonmotor component found by Ogle and Prangen (1953) only amounted to 3% of the total fusional response (for central squares of 1.25°), which is a factor 10 less than the typical values found by Kertesz for central squares of similar size. The maximum fusible vertical fixation disparity usually remains below about 10' - 20' according to Ogle and Prangen, while Kertesz's data would suggest that vertical fixation disparities up to as much as 2° do not disrupt binocular single vision.

The purpose of the present study is to unravel the causes of these large discrepancies, which were not even referred to by Kertesz.

The first discrepancy mentioned above, concerning the stimulus size needed to obtain large fusional responses will be analysed with the aid of an experiment in which fusional responses to a large complex circular stimulus of outer diameter 57°, with 50 horizontal lines and a black square (of side 2.5°) in the middle and a white disk (diameter 10') at the centre of the square (this whole stimulus is identical with the largest stimulus used by Kertesz) are compared with the fusional responses obtained for the central black square with the white disk when the 50 horizontal lines are deleted. The results of this experiment could have practical implications for the work of optometrists: it is much easier to use a special stimulus in a commercially available synoptophore with a viewing angle of 5° - 10° than to build wide-angle synoptophores as suggested by Kertesz (1981).

The second discrepancy, concerning the actual size of the nonmotor component of the fusional amplitude is quite remarkable considering the overall similarity of the stimuli used by Ogle and Kertesz and the apparent validity of the dichoptic nonius-line method used by Ogle and Prangen (1953) to determine the magnitude of objectively present fixation disparities. This validity, though questioned by Kertesz (1981), has in fact been demonstrated by Hebbard (1962), by Crone and Everhard-Halm (1975) and by Duwaer et al. (1981). It can also be inferred from comparison of the data obtained by Riggs and Niehl (1960) by objective measurements and by e.g. Ogle, Mussey and Prangen (1949) with a dichoptic nonius-line technique, and from various other observations (Duwaer and Van den Brink, 1981b). It seems therefore likely that the second discrepancy is closely related to the specific kind of stimulus used by Kertesz, which seems to trigger the occurrence of different types of sensory processes that can bridge larger disparities.

If the nonmotor component of the fusional response can indeed be as large as Kertesz (1981) claims, this would be an extremely important finding and the first confirmation of the often quoted, but never replicated results of Fender and Julesz (1967) suggesting an extension of Panum's fusional area by an order of magnitude under specific stimulus conditions.

Because of the enormeous impact of results of this kind - if indeed true - on our understanding of binocular single vision, it was decided to replicate Kertesz's experiments. A straightforward afterimage method will further be used to determine the relative magnitudes of the motor and nonmotor components of the fusional response. This afterimage method of which the details were developed by the present author (Duwaer, 1981) seems to obviate all the uncertainties, artefacts and errors which are typically encountered when directions of the visual axis are assessed 'objectively' by measuring the angular positions of special contact lenses attached to the eyes as was done by Kertesz (1981).

METHODS

Stimulus

Diapositive copies were made of Kertesz's complex stimulus with and without the 50 horizontal lines (see Fig. 1), and were projected in a darkened room on a homogeneous white screen (dimensions 70° x 60°; resulting mean luminance level 30 cd/m^2) at a distance of 35 cm from the subject's eyes. The magnification of the projection was chosen so that the outer diameter of the stimulus subtended an angle of 57° at the subject's eyes and the side of the central square an angle of 2.5°. The white fixation disk at the centre then had an angular width of 10'. A circular hole of diameter 7' concentric with this disk was drilled in the screen. A photographic flash light (flash duration 20 msec) was mounted behind this hole, and used to imprint afterimages of the hole on the retinae. The stimulus parameter in the experiments was vertical disparity between the images seen by the two eyes, which was introduced with the aid of rotatory prisms directly in front of the subject's eyes. If required, the contribution of each eye to the percept could be checked by flashing dichoptic nonius markers on either side of the fixation disk within the black square. These markers were realized with the aid of LEDs (light-emitting diodes) placed behind pieces of polaroid and holes (diameter 10') drilled in the screen. By suitable choice of the orientation of these pieces of polaroid and those in front of the subject's eyes, the light coming from the LEDs to the left of and above the fixation disk could only be seen by the left eye and light emitted by the LEDs to the right of and below the fixation disk only by the right eye. If both eyes contribute to the percept of the stimulus around the fixation point, all four markers will be seen by the subject when flashed.

Afterimage method

The afterimage method used to determine the magnitude of the fixation disparities, and in general of retinal image displacements between two successive fixation positions, has been described in detail elsewhere (Duwaer, 1981). In short, this method is based on the facts that 1) an afterimage provides a temporary retinal 'landmark' so that the relative positions of successively imprinted afterimages reflect the relative directions of the visual axis (i.e. the lines from the point of fixation to the corresponding image point in the centre of the fovea) during imprinting (see e.g. Ditchburn, 1973), 2) while an afterimage may fade within a few seconds when seen against a background of constant luminance it can be viewed for much longer against a temporally modulated background (in fact, the fluctuating background even regenerates an afterimage that has faded to invisibility when seen against a constant background) and 3) closing of one eye causes the afterimage in that eye to disappear quickly so that the afterimage in the open eye can be observed without interference. The effect of vertical test disparity on the observed fixation

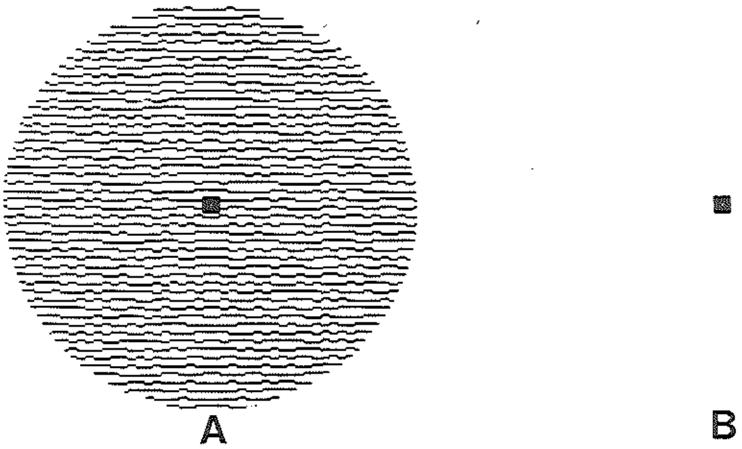

Fig. 1. Schematic representation of the stimuli used in this study. The outer diameter of stimulus A amounted to 57°. The square in the middle of stimulus A and the square in B was of side 2.5°, and had a white disk of diameter 10' at its centre. Stimulus in A is identical with that used by Kertesz (1981).

disparity was determined by imprinting an afterimage in both eyes during binocular observation of the stimulus with disparity, imprinting a second afterimage in both eyes during observation of the stimulus without disparity, and by having the subject estimate the relative positions of the first afterimage with respect to the second for each eye separately. This was done with reference to a scale provided by horizontal and vertical markings at intervals of 15' shown on a TV screen (dimensions 7.4° x 4.9°; mean luminance level 19 cd/m^2; distance from the subject's eyes 200 cm) the luminance of which was sinusoidally modulated (with a frequency of 2.7 Hz and a depth of 100%). The discrepancy between these relative positions in the two eyes is a measure of the fixation disparity introduced by the test disparity in the stimulus.

Experimental procedure

The subject was aligned in the experimental set-up and his head supported by a chin-rest. He then fixed his gaze about 10' to the left of the centre of the central fixation disk of one of the stimuli of Fig. 1. The stimulus contained no vertical disparity between the images seen by the two eyes. The vertical disparity was then increased gradually with the aid of prisms as described above until either the fusional amplitude or some smaller value of the disparity was reached. The fusional amplitude was approached slowly at a rate that varied between 5' of vertical disparity per 5 seconds and 5' per 20 seconds. Fifteen seconds after that the fusional amplitude had been reached, a pair of afterimages was imprinted on the retinae of the subject's eyes by actuating the photographic flash light (the luminance of which was attenuated by a factor 10). The 15 sec delay was introduced in order to allow the system controlling vertical vergence eye-movements enough time to complete its response to the vertical disparity and to test whether the fusional response was stable: just above the fusional amplitude, the eyes return gradually towards a more aligned position and diplopia emerges in the whole stimulus. Subsequently, the vertical disparity was removed and the subject waited at least 15 seconds until the whole test stimulus was perceived as unequivocally single; the afterimages had then already been invisible for about 10 seconds. A second pair of afterimages was then imprinted on the retinae (without attenuation of the luminance of the flash light) while the subject looked at the centre of the central fixation disk. He then looked quickly at the TV screen with its fluctuating luminance, closed the left eye and memorized which of the two afterimages in the right eye was produced second. He then did the same for the afterimage in the left eye by closing the right eye. It may be mentioned for the sake of clarity that the first afterimage which had been faded to invisibility is regenerated by the fluctuating luminance. The second afterimage could be recognized from its higher brightness, its larger diameter and its position: it was further to the left because of the slightly different fixation positions used. The subject then estimated the vertical coordinate of the centre of the first afterimage with reference to the centre of the second afterimage, using the scale with 15' graduations shown on the TV screen. This was done for the left eye by closing the right eye and for the right eye by closing the left eye. The subject plotted these observed coordinates on graph paper. He was advised to maximize the accuracy of his observations by using all the available time (about 1 minute) and by looking at the afterimages in the left eye and right eye alternately. The diameter of the second and first afterimage was about 8' and 4' respectively while the coordinates were being estimated. The discrepancy between the vertical coordinates of the first afterimage in the left and the right eye was taken as a measure of the fixation disparity introduced by the test disparity in the stimulus, i.e. the value of the nonmotor component of the fusional response but (by definition) of opposite sign. The procedure described above was carried out 10 times for each stimulus condition used. Each fixation disparity presented is the mean of the 10 experimental values obtained.

The measure of the fixation disparity under the specific stimulus conditions used was calibrated in control experiments in which the two afterimages in each eye were formed simultaneously, using masks with two holes for each eye with known physical relative vertical discrepancies between the eyes instead of by successive flashes through a mask with one hole with unknown vertical discrepancies due to changing vertical alignment of the eyes during the experiments. The results of this control experiment are given in Fig. 2 for the two test subjects used in this study. It may be concluded from these data that the vertical discrepancy in minutes of arc is equal to 92% of the estimated discrepancies in subject ALD and 81% in subject JvZ. It should be noted that the physical discrepancy tends to be overestimated.

RESULTS

The data were obtained from subject ALD (the author) who is highly practised in initiating motor responses to disparities and in judging singleness of bi-

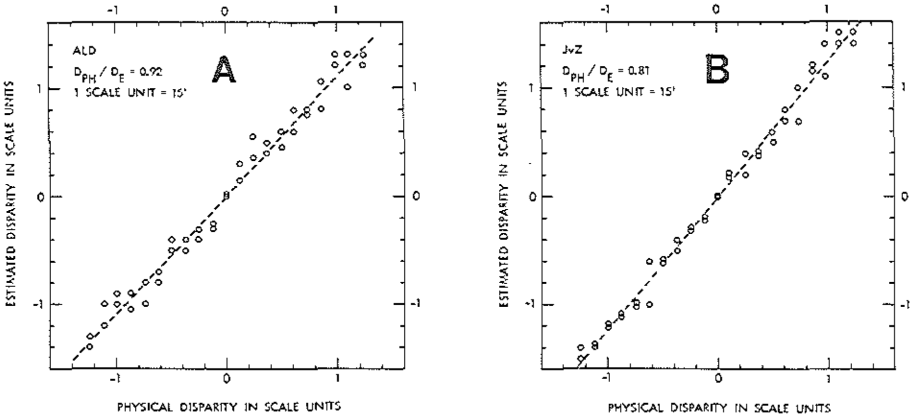

Fig. 2. The estimated vertical disparity as a function of the physical relative vertical disparity, in scale units (one physical scale unit amounted to 15'). The dotted line was fitted to the experimental data points by linear regression. A) Results for subject ALD, B) results for subject JvZ.

nocular vision, and in subject JvZ who was unpractised. Both subjects have normal binocular vision with good stereopsis (threshold $< 30''$ according to the TNO test with random-dot patterns, distributed by Laméris, Utrecht, The Netherlands). Subject ALD was corrected for myopia with -0.75 dioptres for both eyes. Subject JvZ was emmetropic. The monocular Landolt-C visual acuities of both subjects were better than 5/4.

Fusional amplitudes

The largest disparity at which the fusional response remained stable was taken as the 'fusional amplitude'. At this fusional amplitude the subjects perceived a marked departure from singleness in the central fixation disk. The upper and lower parts of the square and the horizontal lines (if present) near the square exhibited restlessness, blurring and binocular rivalry. In other words, at the fusional amplitude the singleness of the stimulus is already deteriorating in the central part of the visual field. It has been argued elsewhere (Duwaer and Van den Brink, 1981a) that the lower limit of 'the' diplopia threshold must already have been passed under these conditions. Activation of the four dichoptic nonius markers confirmed that both eyes contributed to the percept at the fusional amplitude. These markers were however misaligned in the vertical direction, indicating the occurrence of a vertical fixation disparity. The magnitude of the disparity estimated on this basis was found to agree with that determined with the aid of afterimages (see next section).

Increasing the stimulus disparity to a constant level just above the fusional amplitude resulted in a gradually increasing amount of diplopia: the square was seen as elongated in the vertical direction while the separation between the two perceived images of the central fixation disk increased. When the horizontal lines were present, the deterioration of the singleness of the horizontal lines surrounding the square became alternately better and worse. The elongation of the square in the vertical direction and the increase in separation between the two perceived central disks then tended to stop at positions where the deterioration of the singleness of the horizontal lines was relatively slight. The vertical separation between the two perceived central disks under these conditions remained constant, sometimes at about 1° but mostly at about 2° - 2.5°. In the latter case, the vertical side of the 'square' was about twice as long as the horizontal side. What seemed to happen here was that the eyes, unable to align on corresponding parts of the stimulus, started to align on similar non-corresponding parts. Kertesz's stimulus contains an abundance of these similar non-corresponding parts, because of the periodicity of the horizontal lines in the vertical direction.

The observed fusional amplitudes were 5.2° (right hypo) - 6.3° (right hyper) in subject ALD and 2.9° (right hypo and hyper) in subject JvZ for the 57° wide complex stimulus used by Kertesz (1981). Right hypo vertical disparities are disparities for which the stimulus presented to the right eye was displaced in a downward direction, whereas the stimulus seen by the left eye was displaced in an upward direction from zero disparity viewing conditions. We wish to emphasize that it took our subjects, just like the subject tested by Ellerbrock, several minutes to achieve this high performance which necessitated looking at the stimulus with full concentration while trying to blink as little as possible. Otherwise, the fusional amplitudes found were 1° - 2° lower. The values of the fusional amplitude found here agree with those reported by Kertesz (1981) but are substantially higher than the typical values reported by Ogle

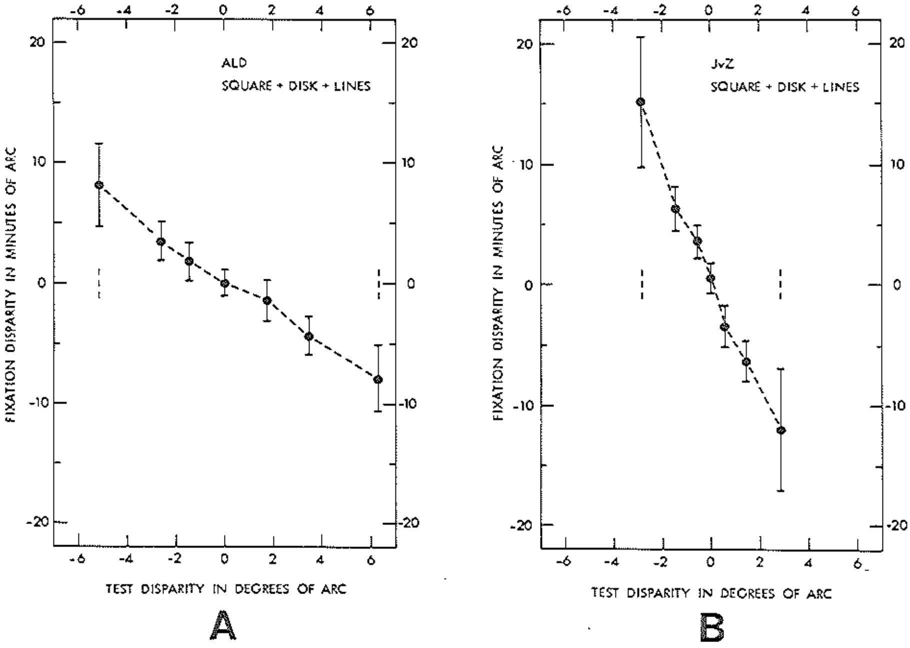

Fig. 3. Fixation disparity (in minutes of arc) as a function of the disparity (in degrees of arc) in the stimulus of Fig. 1A for subject ALD (A) and for subject JvZ (B). The length of the vertical bars through the experimental points is equal to twice the standard deviation (n=10). The broken vertical bars represent the fusional amplitudes. Positive vertical disparities are disparities for which the stimulus presented to the right eye had a higher position than the stimulus presented to the left eye.

and Prangen (1953). This is not surprising, as the vertical disparity was increased much faster in their study. Deletion of the 50 horizontal lines to leave a simple square of side 2.5° at the centre of the homogeneous background field (see Fig. 1A, B) resulted in fusional amplitudes of 4.1° - 5.2° for subject ALD and 2.3° for subject JvZ. These values are in agreement with those reported by Ellerbrock (1949). It is noteworthy that the fusional amplitudes did fall under these conditions but only by 25%. This implies that the advantages gained by using wide-angle stimuli, which are much more of nuisance to work with, are very slight and that a simple black square of side 2.5° can elicit almost the same fusional amplitude as a much larger complex stimulus consisting of as many as 50 horizontal lines.

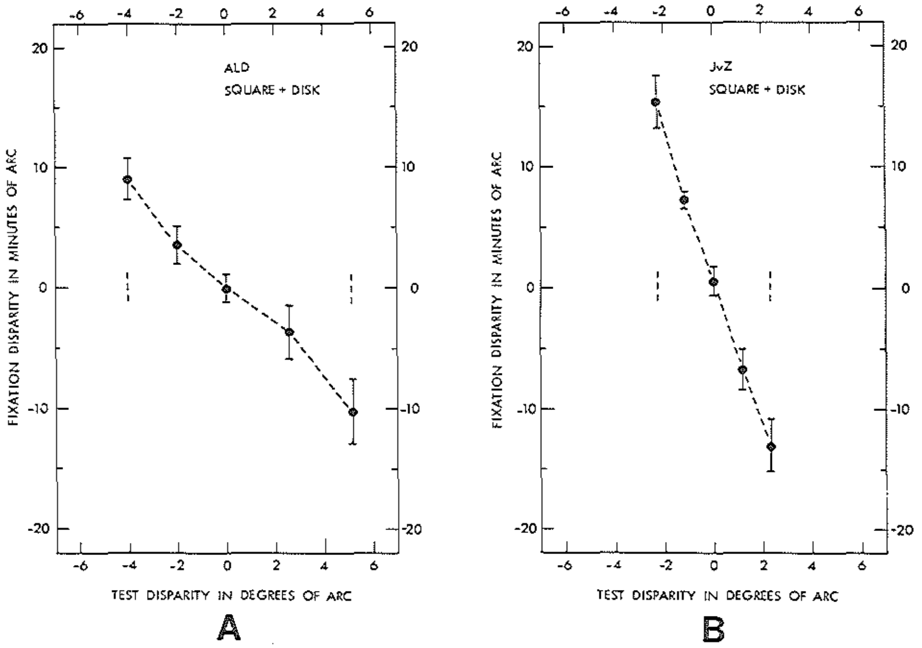

Fig. 4. Fixation disparity (in minutes of arc) as a function of the disparity (in degrees of arc) in the stimulus of Fig. 1B. For further details, see legend to Fig. 3.

Nonmotor component of fusional response

The nonmotor component of the fusional response as estimated by the afterimage method is plotted with opposite sign as fixation disparity as a function of the vertical disparity in Fig. 3 for Kertesz's complex stimulus (see Fig. 1A), and in Fig. 4 for the central square remaining when the 50 horizontal lines of this complex stimulus are removed (see Fig. 1B).

It may be seen from the fixation disparity curves in these figures that the nonmotor component increases more or less linearly with the vertical disparity.

For the complex stimulus with horizontal lines, the maximum vertical fixation disparity at which a stable fusional response is found amounts to 8' for subject ALD and 15' for subject JvZ (see Fig. 3). These values are a factor 7-17 lower than the typical values reported by Kertesz (1981). Our values of the fixation disparities indicate that the nonmotor component of the fusional response amounts to 2% for subject ALD and 8% for subject JvZ, i.e. a factor 3-20 less than the typical values found by Kertesz (1981). It may be seen from

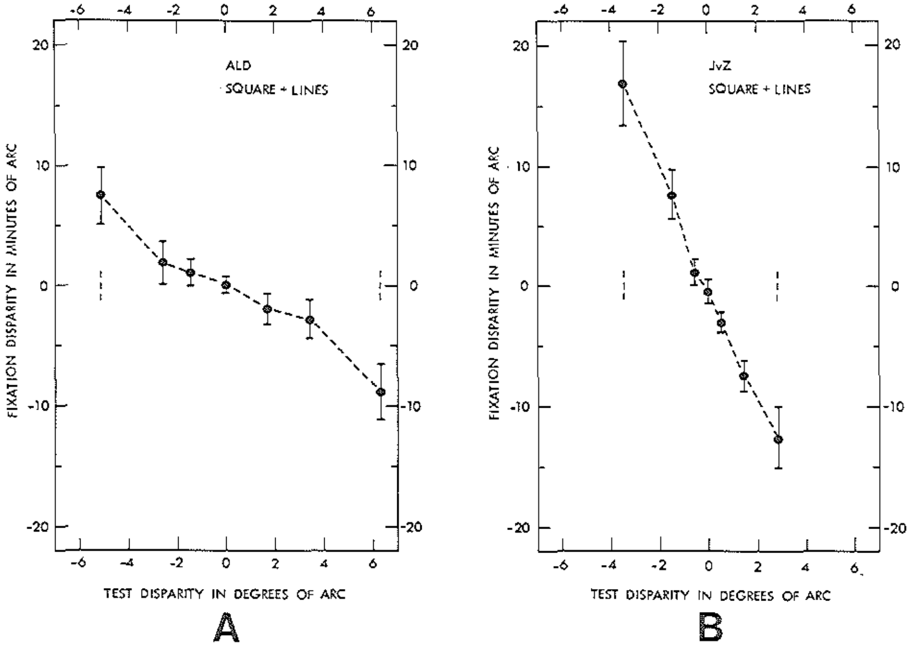

Fig. 5. Fixation disparity (in minutes of arc) as a function of the disparity (in degrees of arc) in the stimulus of Fig. 1A but the white fixation disk deleted from the centre of the square. For further details, see legend to Fig. 3.

Fig. 4 that the relative contribution of the nonmotor component to the total fusional response increases slightly when the 50 horizontal lines of the stimulus are removed, because the maximum vertical fixation disparity remains about the same while the fusional amplitude falls slightly.

The influence of foveal cues for the presence of disparity

The results of the present study indicate that at the fusional amplitude for the large complex stimulus as used by Kertesz, singleness of vision is clearly disrupted in the fovea, less clearly disrupted at eccentricities of 1^{o} - 2^{o} and not at all disrupted at larger eccentricities. One might therefore argue that the maximum fusible fixation disparity is relatively low in the present study, as the subjects noticed clear departure from singleness in the fovea. This is, however, not the case as may be concluded from the results of a control experiment shown in Fig. 5. This control experiment was performed using

Kertesz's complex stimulus without the central fixation disk. The centrally fixated square was now totally black, so that the subject had no foveal cues at all about the presence of fixation disparity. In spite of the absence of those foveal cues, about the same maximum fusible fixation disparities were found.

DISCUSSION

The major findings of the present study may be summarized as follows:

-The fusional amplitudes for vertical disparity in a complex stimulus with a diameter of 57° consisting of 50 horizontal lines, a central square of side 2.5° and a white fixation disk of diameter 10' at the centre of the square were found to amount to 3° - 6° the nonmotor component of which was only 8' - 15', i.e. 2%-10% of the total fusional response;

-Deletion of the 50 horizontal lines, leaving only the small square with the fixation disk in its middle lowered the fusional amplitude by only 25%, while the absolute value of the nonmotor components remained the same;

-Deletion of the central fixation disk, thus removing foveal cues for the presence of a nonmotor component, did not increase the nonmotor component.

These findings agree with those reported by Ogle and Prangen (1953) and Ellerbrock (1949), but differ fundamentally from the data recently published by Kertesz (1981).

Possible explanations of discrepancies

One possible explanation for the above-mentioned discrepancies might be that Kertesz did not allow the vergence system sufficient time to settle down when measuring motor responses. However, the practice to measure stabilized responses is well recognized in this field; indeed, this practice was explicitly taken into account by Kertesz in a previous study (Perlmutter and Kertesz, 1978), and it is highly unlikely that he would have overlooked it here.

Alternatively, one might argue that the discrepancies could be ascribed to the use of subjective methods to determine the nonmotor component of the fusional response in the present study and in that of Ogle and Prangen (1953). The assessment of vertical fixation disparity in the present study by the (subjective) afterimage method, giving results similar to those obtained by the (subjective) dichoptic nonius-line method used by Ogle and Prangen (1953), must however be regarded as extremely reliable. The afterimage method may be characterized as a direct method since it measures successive directions of the visual axis using retinal landmarks. It is worth noting that the dichoptic nonius line method as such is less direct than the afterimage method, as it assumes a rigid binocular correspondence in the test subject. The latter is, however, commonly encountered in subjects with normal binocular vision.

Objective recording of fixation disparities using special contact lenses attached to the eyes is less direct than it seems, and moreover troublesome to the test subject and thus less reliable. This method assumes a one-to-one correspondence between the angular position of the contact lens and the direction of the visual axis. This assumption is only valid when there is no slippage whatsoever of the contact lens and no eye-ball deformation caused by the lens, when the measurements are properly corrected for angular magnification or minification caused by any optical aids worn by the subject (Ogle, 1971), and when artefacts due to head translation are kept to a minimum. Moreover, the special contact lenses place an unnatural load on the subject and are likely to interfere with the visual apparatus and to distract the subject from his visual task. Thus, if the cause of the discrepancies is some artefact due to the method used for measuring the motor component of the fusional response, in our opinion this artefact is more likely to be associated with the objective measurement, than with the afterimage method.

If the discrepancies are not due to some artefact in the measured motor component of the fusional response, the only other possibility would seem to be confusion about the fusion criterion. It has been shown in a previous study that the maximum fusible retinal disparity depends strongly on the fusion criterion used: the transition from unequivocal singleness to unequivocal doubleness is gradual, a whole range of intermediate percepts being observed between the two extremes (Duwaer and Van den Brink, 1981a). Of course, the maximum fusible retinal disparity depends even more strongly on the fusion criterion when the stimuli cover a large part of the visual field; this is illustrated by the fact that in the present study, at the fusional amplitude for the large complex stimulus of Fig. 1A the singleness of vision was found to be clearly disrupted in the fovea, less clearly disrupted at eccentricities of 1° - 2°, and to be preserved at larger eccentricities. The subject's criterion for fusion in Kertesz's (1981) study was that the percept of the stimulus lines should be 'simultaneously unified, single and straight in appearance'. This criterion does not mention the appearance of the central fixation disk (which was seen double by our subjects) nor does it specify whether or not the singleness of the square and lines differed from the singleness of the square and lines without vertical disparity (which was the case in the present study).

The fusion criterion used in the present study was in fact determined by the system controlling vertical vergence eye-movements. Up to a certain fixation disparity a stable motor response was elicited with, as we have mentioned, a certain disruption of singleness near the centre of the visual field, but with the horizontal lines outside the square being seen as 'unified, single and straight in appearance' in line with Kertesz's fusion criterion. More or less stable motor responses involving perception of the horizontal lines as unified, single and straight were also obtained at larger fixation disparities (up to 2.5°). However, these responses were rejected because they were found to be based on correlation of noncorresponding horizontal lines which are abundantly present in the complex stimulus used by Kertesz. One possible reason for the discrepancy between Kertesz's data on the one hand, and the results of the present study and e.g. Ogle and Prangen (1953) on the other, may therefore be that Kertesz did not exclude fusional responses based on correlation of similar noncorresponding parts of the stimulus with a vertical disparity which is (much) smaller than the test disparity, whereas these fusional responses were excluded in the other two studies.

Fusional response to horizontal disparity

Kertesz (1981) also studied the fusional response to *horizontal* disparity. Two major problems encountered when the horizontal disparity is varied are the perception of stereoscopic depth and blurring of the image due to accomodation-convergence coupling. These problems may well bias subjects towards use of very lenient fusion criteria. Moreover, voluntary convergence on an intermediate relative depth or fusion of similar noncorresponding parts of the stimulus may also occur even when the physical stimulus is just a single line. When analysing the large maximum fusible *horizontal* fixation disparities that may be obtained during forced convergence or divergence using only horizontal disparity as stimulus, one must bear these complications in mind.

ACKNOWLEDGEMENTS

I would like to thank Prof. Dr. G. van den Brink, Dr. C.M.M. de Weert and Mrs. A.E.H. Peters for helpful discussions, Dr. R.H. Bathgate for improving the English, and the Netherlands Organization for the Advancement of Pure Research (Z.W.O.) for financial support.

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V

VALIDITY OF THE SUBJECTIVE NONIUS-LINE METHOD TO DETERMINE OCULAR ALIGNMENT

Chapter V deals with the validity of the subjective nonius-line method which is commonly used for obtaining accurate information about (motor) ocular alignment. This method has been applied in the experiments described in Chapter III.
In this nonius-line method, the perceived misalignment of two separate, physically aligned lines - each seen by one eye only - is assumed to be equal to the amount of ocular misalignment.
Data obtained by this subjective method on the ocular alignment in the vertical direction have been compared with objective recordings of this ocular alignment under the specific stimulus conditions that the subjective method was used in the present study.

5.1 COMPARISON OF SUBJECTIVE AND OBJECTIVE MEASUREMENTS OF OCULAR ALIGNMENT IN THE VERTICAL DIRECTION

A.L. Duwaer, G. van den Brink, G. van Antwerpen, C.J. Keemink*

ABSTRACT

Ocular alignment on a stimulus with a vertical disparity of up to 20' has been measured by the subjective nonius-line method and by objective recording of the position of the eyes.

Both methods indicate that the vertical disparity is almost entirely eliminated by appropriate vergence eye-movements.

The results strongly suggest that the subjective nonius-line method is valid for determination of the vertical alignment of the eyes, just as the results of previous studies suggest it to be valid for the determination of horizontal alignment and torsional alignment.

INTRODUCTION

The 'subjective' nonius-line method is commonly used to obtain information about ocular alignment. In this method, the perceived misalignment of two physically aligned dichoptic lines - each seen by one eye only - is assumed to be equal to the amount of ocular misalignment. This subjective method has the major advantage of providing a way of estimating ocular misalignments down to 0.3' 1) without the burdensome use of special contact lenses held to the eyes by suction, with all the accompanying errors and artefacts this 'objective' method involves. Various forms of the nonius-line method are used both in clinical practise (Ogle, Martens and Dyer, 1967; Sheedy, 1980) and in fundamental re-

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search (Kidd, Frisby and Mayhew, 1979; Frisby and Mayhew, 1980; Duwaer and Van den Brink, 1981a, 1981b).

The validity of the nonius-line method for determining *horizontal* alignment of the eyes has been demonstrated by Hebbard (1962) by direct comparison of the results of objective and subjective measurements, and can be inferred from a comparison of subjective measurements by Ogle et al. (1967) on the one hand and objective measurements by Riggs and Niehl (1960) on the other. The validity of the nonius-line method for measurement of *torsional* alignment has also been demonstrated by direct comparison of the results of objective and subjective measurements (Crone and Everhard-Halm, 1975). However, the validity of the nonius-line method for determination of *vertical* alignment can so far only be made plausible by comparison of subjective data (Ogle and Prangen, 1953) with objective data of relatively low accuracy from other studies (Perlmutter and Kertesz, 1978; Houtman, 1979), or on the basis of various other observations (Duwaer and Van den Brink, 1981a).

The purpose of the present study is to test the validity of the subjective nonius-line method for determination of the *vertical* alignment of the eyes by direct comparison of subjective data with objective recordings of ocular alignment obtained by the magnetic-field technique proposed by Robinson (1963) while using the special contact annuli with sensor coils held to the eyes by suction that were developed by Collewijn, v.d. Mark and Jansen (1975).

METHODS

Stimulator

The stimulator has been described in detail elsewhere (Duwaer and Van den Brink, 1981b). In short, it is an electronic stereoscope consisting of two HP 1321A displays (white P31 phosphor) mounted 105 cm from the subject's eyes with a white background (mean luminance level 3 cd/m^2; dimensions 15° x 15°). The line stimuli were generated on the displays by appropriate electronic circuitry.

Stimulus

The stimulus is depicted in Fig. 1. Its luminance was adjusted to 1.8 log units above the (contrast) perception threshold. The line width amounted to 1.2'. The test stimulus consisted of a vertical line of length 10° and two parallel horizontal lines of length 2° at a separation of 2°. The nonius lines at the centre had a length of 20' and a lateral separation of 6'. The parameter in the experiments was the vertical disparity between the test stimuli presented to the two eyes which was controlled with an accuracy of 0.1'. The vertical disparity is defined as positive when the stimulus presented to the right eye is higher than that presented to the left eye. The vertical disparity between the nonius lines could be varied independently.

The subject was instructed to look at the portion of the vertical line between the two nonius lines.

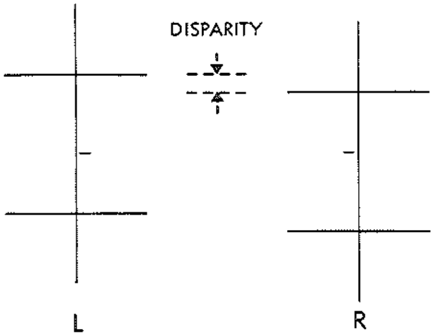

Fig. 1. Schematic representation of the test stimuli presented to the left (L) and right (R) eye, consisting of a vertical line and two parallel horizontal lines for each eye. The test stimulus depicted contains a negative vertical disparity, i.e. by definition the stimulus presented to the right eye was lower than that presented to the left one. The nonius lines at the centre were used to provide a subjective estimate of ocular misalignment. See text for further details.

Subjective nonius-line method for measurement of ocular alignment

The introduction of vertical disparity in the test stimulus resulted in a perceived vertical misalignment of the physically aligned nonius lines. This misalignment was determined by getting the subject to adjust the vertical disparity between the nonius lines until optimum alignment is perceived. If the nonius-line method is valid, this vertical disparity is equal to the disparity eliminated by appropriate vergence eye-movements in response to the vertical disparity in the test stimulus (see e.g. Duwaer and Van den Brink, 1981a). Experiments showed that the vertical disparity between the nonius lines should then be equal within 3% to the vertical disparity in the test stimulus in the range between -20' and +20', so that the nonius lines remain approximately in line when the same vertical disparity was introduced in both the test stimulus and the nonius lines. This fact was made use of to obtain a fast subjective estimate of ocular alignment during objective measurements with contact annuli held to the eyes by suction. The subject's task was then reduced to assessing whether the lines had remained in line during the sampling period of the objective measurements, and reporting this finding.

Objective method for measurement of ocular alignment

The eye positions were recorded by the method described in detail by Robinson (1963). Scleral contact annuli with an induction coil were attached to the eye. A vertically oriented electromagnetic field (frequency 14.3 kHz) was generated around the head by two square coils of side 68 cm with a vertical separation of 73 cm. An AC potential was induced in each ocular coil, with a magnitude and phase related in a simple manner to the angular position of that coil in the vertical direction. A voltage proportional to the sine of the angular position (which is proportional to the angular position itself within 0.02% for the maximum range of -2° to $+2^{\circ}$ used) was obtained by suitable buffering (with PAR 116 transformers), amplification and phase-sensitive detection (with the aid of two PAR 124A Lock-in amplifiers). The two voltages were recorded on a UV recorder and sampled with a frequency of 200 HZ by a 10-bit AD convertor controlled by a M6800 microprocessor. Samples taken during the time that the Lock-in amplifiers were in overload, usually due to blinks, were deleted. The microprocessor determined the differences between corresponding samples of the two voltages (obtained with a 20 µsec intersample time). This difference signal - indicating the difference between the angular positions of the two ocular coils as a function of time - was fed to the UV recorder, while the microprocessor determined the mean values of the voltages measured during 10-second periods. The standard deviation of the noise introduced in the difference signal by the recording system amounted to 0.2'.

The objective method described above assumes a one-to-one correspondence between the voltage induced in the sensor coil of the contact annulus attached to the eye and the direction of the visual axis (i.e. the line from the point of fixation to the corresponding image point in the centre of the fovea) for a fixation stimulus at a constant position in space relative to the fixating eye. This is only true when the contact annulus does not slip across the cornea, when its shape is precisely constant, when there is no deformation of the eye caused by the suction with which the annulus is held to it and when head movements are rigorously excluded. In our set-up, the subject's head was fixed using a bite-board. However, small head displacements, e.g. due to breathing, are still possible. In fact, artefacts of ±3' due to head displacements were found experimentally in the difference signal when the subject was looking at the stimulus on the display screens at a distance of 105 cm. These artefacts are due partly to inhomogeneity of the magnetic field and partly to changes in the position of the stimulus relative to the eye. It is important to realize that the latter changes in position occur equally for both the test stimulus and the nonius lines so that they will not affect the subjective measures of ocular alignment obtained by the nonius-line method when the eyes are allowed ample time to align to the test stimulus. The major problem in most experiments was, however, that the voltages induced in the ocular coils indicated that the mean direction of the visual axis (as determined during the 10-seconds periods) was changing by up to 2° during a 15-minute session, even though the subject fixed his gaze on the same position in space. Now it is known that the mean direction of gaze should be reproducible within 5' to 10' when the subject's head is fixed with a bite-board (see e.g. Collewijn et al., 1975; Steinman, Cushman and Martins, 1981). This was in fact found to be true for our test subjects too, on the basis of data obtained by an afterimage technique (Duwaer, 1981a) and by quite a different technique described by Drysdale (1975) [2]. It was, therefore, concluded that those changes in the induced voltages do *not* reflect changes of gaze by up to 2°, but rather artefacts due to slippage of the contact annulus, gradual changes in the shape of the annulus due to stresses built up when it is initially pressed down on the eye, and deformation of the eye itself; the last-mentioned effect could in fact often be noticed by the subject due to the resulting distortion of the perceived visual field.

The above considerations led us to rely on the objective data only when the mean angular positions of the eyes measured during the 10-second experimental periods was reproducible to within 10' for the stimulus without disparity during the course of the experiment. Unfortunately, this occurred only rarely (in about 20% of the experiments).

Experimental procedure

To determine the vertical misalignment of the eyes in response to the vertical disparity in the test stimulus by the *subjective* method, the subject was aligned in the experimental set-up with his head fixed by the bite-board. He made four adjustments of the vertical disparity between the nonius lines to obtain optimum alignment for each test disparity.

The procedure was more elaborate when the *objective* method was used. First a drop of anaesthetic (Novesine) was applied to the eyes. Each annulus was then wetted with Ringer solution, placed with its edge on the limbus of the cornea and pressed firmly down. The amount of pressure applied appeared to be quite critical. Too much pressing resulted in a deterioration of visual acuity so that the subject could not perform any visual task more exacting than 'counting fingers', while the annulus would slip easily when not pressed down firmly enough. The subject was then aligned in the experimental set-up and his head fixed with the bite-board. The induced voltages were then brought into the working range of the recording equipment by adjusting the angular position of compensation coils in series with the ocular coils. The induced voltages were calibrated by having the subject look at the line intersections 1° above and below the centre of the stimulus (see Fig. 1). The induced voltage was then determined for various values of the test disparity introduced in the test stimulus and between the nonius lines. Each experimental session lasted at most 20 minutes. A major problem was the gradual deterioration of visual acuity in the course of the session and even between two successive blinks. This was most probably a result of the disturbance of the moisture content of the cornea due to the presence of the annulus. This deterioration of visual acuity was minimized as follows. Before each sampling period, the subject first closed his eyes for about 1 minute, then opened them and looked at the stimulus for at least 15 seconds in order to give them ample time to align to the stimulus. He now blinked, and gave a signal as soon as the perceived nonius lines were sharp and in line. The angular position of his eyes was then sampled for 10 seconds, during which time he tried to avoid blinking as much as possible. He then closed his eyes and reported whether the nonius lines had remained in line during the 10-second sampling period. Usually they did remain in line indicating eli-

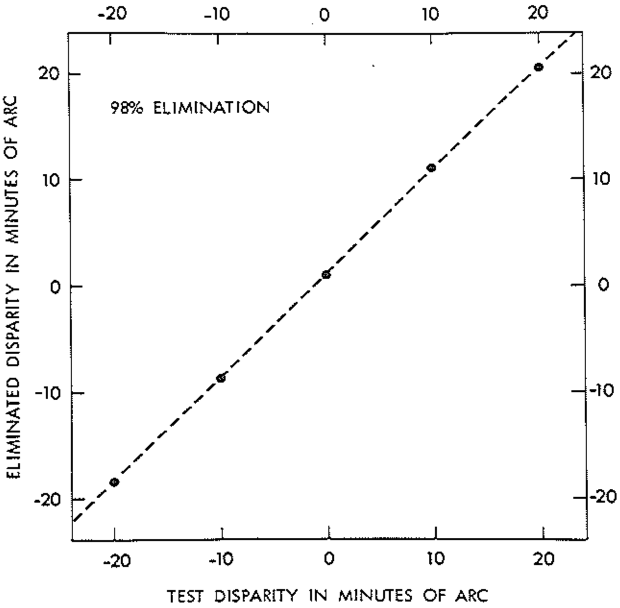

Fig. 2. Disparity eliminated by vergence eye-movements, as measured by the vertical disparity that had to be introduced between the nonius lines in order to obtain optimum alignment as a function of the physical vertical disparity in the test stimulus. The standard deviations of the mean (n=4) are smaller than the size of the symbols. The dotted line through the experimental points, obtained by linear regression, has a slope of 0.98; this indicates that 98% of the test disparity is eliminanated by vergence eye-movements.

mination of the vertical disparity by vergence eye-movements (this is the basic assumption on which the subjective nonius-line method rests). In the relatively rare cases where they did not remain in line, the data were rejected. It may be mentioned that this lack of alignment was always found to be associated with a blurring of the perceived stimulus. It was noticed that the nonius-lines tended to be less accurately aligned when the suction-type contact annuli were on the eyes than without them.

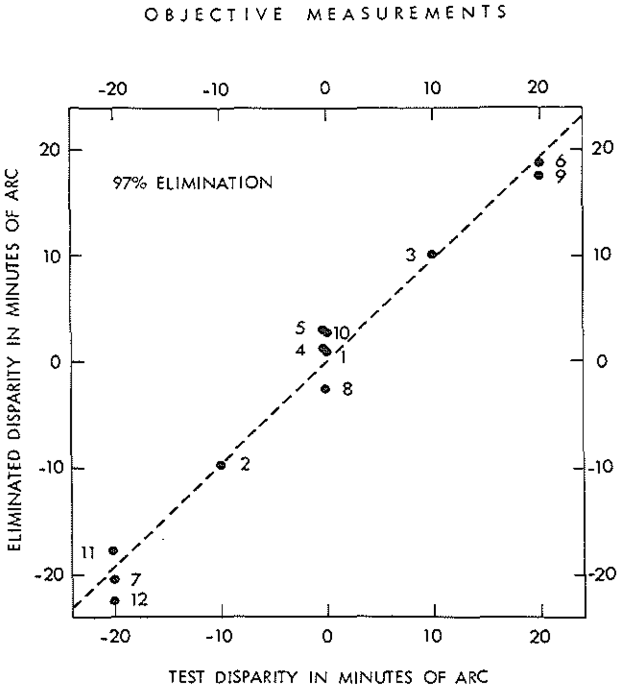

Fig. 3. Vertical disparity eliminated by vergence eye-movements as measured by objective recordings, as a function of the test disparity. The position of the vertical scale relative to the experimental points was arbitrarily chosen in such a way that the (dotted) regression line through the points passed through the origin. The numbers next to the experimental points indicate the sequence in which they were obtained. The regression line has a slope of 0.97, indicating 97% elimination of the test disparity by vergence eye-movements.

RESULTS AND DISCUSSION

The results obtained by the subjective method are presented in Fig. 2, and those by the objective method in Fig. 3. Some typical eye-position recordings are plotted in Fig. 4. 3).

The subjective data indicate that, apart from an offset of 1', 98% of the test disparity introduced is eliminated by appropriate vertical vergence eye-movements; this finding agrees with previous reports obtained with the aid of dichoptic nonius lines (Ogle and Prangen, 1953; Duwaer and Van den Brink, 1981a) or by an afterimage method (Duwaer, 1981b). The above-mentioned offset indicates

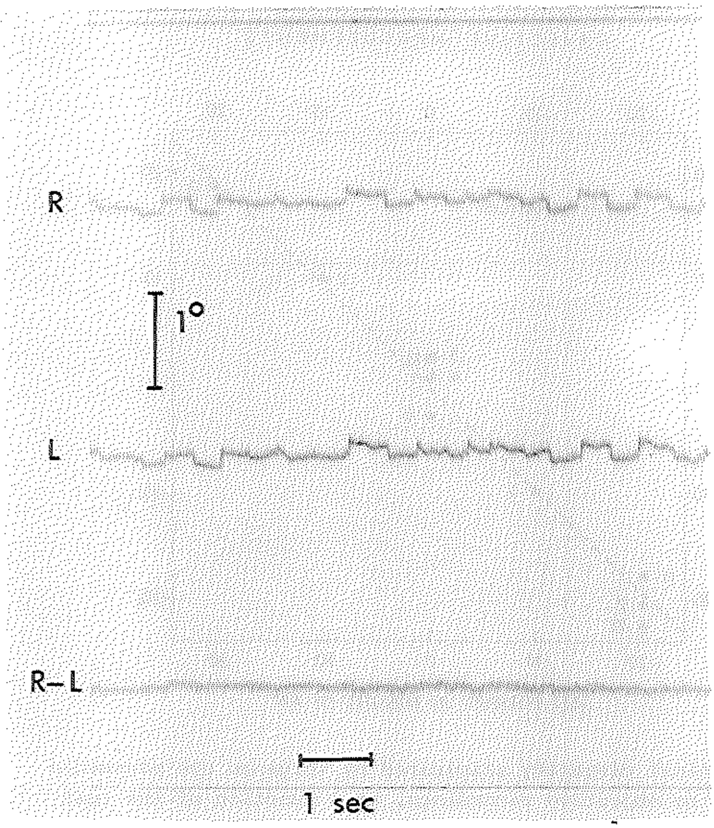

Fig. 4. Some typical recordings of the vertical position of the left eye (L), the right eye (R) and the discrepancy between the two (R-L) during the experiments leading to (experimental point 11 in) Fig. 3.

the occurrence of a small fixation disparity at all test disparities used. [4].

The objective data indicate, in excellent agreement with the subjective data, that 97% of the test disparity introduced is eliminated by vertical vergence eye-movements. It should be emphasized that the position of the vertical scale relative to the experimental points was arbitrarily chosen in such a way that the regression line through these points passed through the origin. This choice was made because the objective data do not provide information about the possible occurrence of a fixation disparity when the stimulus contains no physical disparity. The objective data differed from the subjective data in their much larger scatter up to ± 3'. It has already been indicated in the

Methods section that this scatter reflects experimental errors and artefacts due e.g. to small head displacements and the presence of the contact annuli on the eyes. The latter is supported by the eye-position recordings, which show excellent short-term binocular correlation where these errors and artefacts are likely to interfere less.

CONCLUSION

Subjective and objective measurements of ocular alignment in the vertical direction to stimuli with vertical disparity give practically identical results, within the experimental error. This strongly suggests that the subjective nonius-line method is valid for determination of the vertical alignment of the eyes, just as previous reports suggest it to be valid for the determination of the horizontal alignment (Hebbard, 1962) and torsional alignment (Crone and Everhard-Halm, 1975).

It is further noteworthy that the scatter of the subjective data is appreciably less than that of the objective data.

ACKNOWLEDGEMENTS

We would like to thank Dr. G.J. van der Wildt and Mrs. A.E.H. Peters for helpful discussions, Mr. J.B.P. van Deursen for his technical assistance, Dr. R.H. Bathgate for improving the English, and the Netherlands Organization for the Advancement of Pure Research (Z.W.O.) for financial support.

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NOTES

1. In this paper, all dimensions of stimuli are expressed in degrees of arc and minutes of arc, which for the sake of simplicity are denoted by e.g. 8^o or 2' respectively.

2. This technique permitted visualization of both the position of the foveola and that of the fixation target, by getting the subject to look through a blue filter behind a mask with a small hole (of diameter 1 mm) rotating (at a frequency of about 2 Hz) in a circle (of diameter 3.5 mm) placed at a distance of about 1.5 cm in front of his eye. Under these conditions, the position of the foveola could actually be seen as a dark spot at the centre of an area (of diameter about 1.5^o) without images of retinal blood vessels. When the subject fixed his gaze on the fixation point (which was covered by a scale with 10' graduations), the angular distance between the foveola and the fixation point - apart from small differences in the rotatory movements caused by the rotation of the hole in front of the subject's eye - did not exceed about 10'.

3. The data presented in this paper were obtained from subject ALD (one of the authors), who was corrected for myopia by -0.75 dioptres for both eyes. He had normal (Landolt-C) visual acuity, normal stereopsis (according to the TNO test with random-dot stereograms) and normal binocular single vision.

4. When the test disparity was zero, physically aligned nonius lines were not seen in line: the nonius line seen by the right eye had a lower position than that seen by the left eye. This indicates that the right eye points to a higher position than the left eye.

SUMMARY

The present thesis deals with *binocular single vision*.

By closing one of the two eyes alternately (in particular in the presence of nearby objects), one can easily see that we are confronted with *two* different images of the outside world. Nevertheless, when we look at this world with both eyes we still perceive if for the greater part *singly*. This in spite of the fact that the two images often differ so much that the world would be perceived as clearly double if the same images did not enter the visual system through different eyes but, projected on top of each other, through the same eye. This singleness of binocular vision is accomplished by *motor* processes which use the eye muscles to direct the eyes towards the same point in space, and by *sensory* processes in the brain which avoid *doubling* of the binocular image.

Interpretation of certain types of differences between the images in the two eyes results in *stereopsis* (depth perception) which disappears when one of the eyes is closed. As a result, the observer can assess the occurrence of *these* image differences not only by using the comparatively inconspicuous and inaccurate information provided by image doubling, which is the subject of the present thesis, but also indirectly by using the conspicuous and accurate depth cue. It was decided to avoid this complication by confining the study to those situations where these interfering depth effects did not occur.

The processes underlying binocular single vision have been studied in *psycho-physical* experiments. Subjects were asked to make judgments on the percepts evoked by visual stimuli. The procedures and stimuli chosen were such that they practically guaranteed that the judgments were always based on the same infor-

mation. In this way the mysteriously variable nature of a person's psyche, which is unavoidably involved in the judgments, was restricted.

The material of this thesis consists of eight articles which have been submitted for publication to several international journals. In the present thesis, the articles haven been organized according to their subjects to form four chapters (II - V).

In *Chapter I* (the Synopsis) a brief survey is given of the basic concepts and problems associated with singleness of binocular vision (like disparity, retinal disparity, diplopia, diplopia threshold and stereopsis), followed by the formulation of the two main problems dealt with in the present thesis. These problems concern the nature of the sensory processes underlying binocular single vision and the cooperation between these sensory processes and the corresponding motor processes. A summary is given of the major results of these two problems and a third additional problem touched on in several studies published when the present thesis was nearly finished. The latter problem concerns the way binocular single vision is accomplished under highly demanding conditions. The overall conclusions are given, followed by some concluding remarks on the origin of the present study and the various snags encountered during its execution.

Chapter II deals with an unresolved controversy in the literature when the present study was started. This controversy concerned the nature of the sensory processes underlying binocular single vision. A major traditional view is that these sensory processes are a fusion mechanism eliminating the discrepancies between the images on the retinae of the two eyes (the 'retinal' disparities). According to the opposing view there is no such fusion mechanism.

Three studies were performed in connection with this controversy. In the *first* study the magnitude and nature of the diplopia threshold, that is, the value of the retinal disparity at which binocular single vision ends, have been investigated. In the *second* study the effect of stimulus presentation time on detection and diplopia thresholds for vertical disparities has been determined in order to find out whether the processing is aimed at eliminating or revealing these disparities. In the *third* study the detectability of differences between two different vertical disparities has been determined as a function of the reference disparity in order to find out whether this detectability is so much worse around zero disparity (where binocular single vision occurs) than at comparatively large reference disparities (where diplopia occurs) that it has to be assumed that there is a disparity-eliminating process operating around zero disparity.

The data obtained in these three studies support the view that there is no sensory fusion mechanism in the visual system. Singleness of binocular vision despite retinal disparities seems to be due to (functional) failure of a sensory detection process aimed at revealing the retinal disparities. This failure seems to be primarily due to the tendency of observers to use lenient assessment criteria, to the limited accuracy and reproducibility with which disparity information about image doubling is coded, and to loss of information about the sign of the disparity. The latter reflects the fact that positive and negative retinal disparities - e.g. image in right eye is displaced in an upward direction and in left eye in a downward direction from the corresponding positions in the two eyes, and vice versa - result in the same amount of doubling of the binocular image.

Chapter III describes the results of *two* studies of a major aspect associated with binocular single vision which had not been really tackled before, viz. the cooperation between vergence eye-movements aimed at minimizing retinal disparities by aligning the eyes on the one hand and the processes underlying sensory tolerance to these disparities on the other.

In the *first* study, the magnitude of foveal diplopia thresholds has been compared with the magnitude of 'fixation' disparities occurring spontaneously during continuous binocular fixation due to the limited accuracy of (motor) ocular alignment. Furthermore, the spread of these foveal diplopia thresholds has been compared with the spread of the fixation disparities. In the *second* study, the largest vertical (retinal) disparities (at eccentricities of 0.5 to 4 degrees of arc in the visual field) that do not cause image doubling have been compared with the corresponding smallest vertical (retinal) disparities that can initiate vergence eye-movements. In both studies, a subjective nonius-line method was used to obtain data on ocular alignment (*cf.* Chapter V).

A remarkable finding was that vergence eye-movements can be initiated by vertical disparities as small as the angular distance between the centres of neighbouring retinal receptors.

The data obtained in the two studies suggest that the key-factor in the co-operation between motor and sensory processes underlying binocular single vision is that the sensorimotor system controlling vergence eye-movements in response to retinal disparities is more sensitive and accurate than the sensory system controlling the psychophysical assessment of these disparities in terms of image doubling. Retinal disparities, especially those around the fixation point, are thus continuously motorially eliminated by vergence eye-movements with a more than sufficient accuracy.

Chapter IV deals with binocular single vision under highly demanding conditions.

When the present thesis was nearly finished, several studies were published claiming a quite surprising reduction of the accuracy of (motor) ocular alignment on a visual stimulus and a rise in the sensory tolerance to retinal disparities by up to one order of magnitude under two highly demanding conditions, viz. binocular fixation during active head rotation and forced vertical divergence of the eyes.

These experiments were replicated in two studies using a specially designed afterimage method to measure ocular alignment instead of the 'objective' method used in the above-mentioned studies which is based on the use of special suction-type contact lenses on the eyes.

Under the highly demanding conditions, the ocular alignment on the stimulus was found to remain an order of magnitude better than previously reported.

Chapter V deals with the validity of the subjective nonius-line method which is commonly used for obtaining accurate information about (motor) ocular alignment. This method has been applied in the experiments described in Chapter III.

In this nonius-line method, the perceived misalignment of two separate, physically aligned lines - each seen by one eye only - is assumed to be equal to the amount of ocular misalignment.

Data obtained by this subjective method on the ocular alignment in the vertical direction have been compared with objective recordings of this ocular alignment under the specific stimulus conditions that the subjective method was used in the present study.

The results strongly suggest that the subjective nonius-line method is valid for determination of the vertical alignment of the eyes, just as the results of previous studies suggest it to be valid for the determination of horizontal alignment and torsional alignment.

SAMENVATTING

Dit proefschrift handelt over het *enkelvoudig waarnemen met twee ogen*.

Door afwisselend één van de twee ogen te sluiten kan (vooral in aanwezigheid van nabije objecten) duidelijk gezien worden dat we *twee* verschillende beelden van de buitenwereld "binnen" krijgen. Kijken we nu met beide ogen dan wordt deze buitenwereld meestal toch grotendeels *enkelvoudig* waargenomen. Dit, ondanks het feit dat de twee beelden vaak zoveel verschillen dat de buitenwereld duidelijk dubbel waargenomen zou worden als dezelfde twee beelden niet via verschillende ogen maar op elkaar geprojekteerd via hetzelfde oog binnen zouden komen. Dit enkelvoudig waarnemen komt tot stand door "*motorische*" processen die er met behulp van de oogspieren voor zorgen dat de twee ogen zo goed mogelijk dezelfde kant opkijken, en door "*sensorische*" processen in de hersenen die verdubbeling van het met twee ogen waargenomen beeld voorkomen.

Interpretatie van een bepaald soort beeldverschillen leidt tot *stereopsis* (diepte zien) die wegvalt als één van de twee ogen gesloten wordt. De waarnemer kan daardoor het optreden van *deze* beeldverschillen niet alleen vaststellen door te letten op relatief onopvallende en vage beeldverdubbeling, wat het onderwerp van dit proefschrift is, maar ook indirect aan de hand van opvallende en nauwkeurig waar te nemen diepteverschillen. Besloten is om deze complicatie te vermijden door het onderzoek te beperken tot die situaties waarin stereoscopische diepte percepten niet optraden.

De processen die ten grondslag liggen aan het enkelvoudig waarnemen met twee ogen zijn bestudeerd in *psychofysische* experimenten. Er werd aan proefpersonen gevraagd om uitspraken te doen over percepten opgewekt door visuele stimuli. De procedures en stimuli werden zo gekozen dat ze praktisch garandeerden dat de uitspraken altijd op dezelfde informatie gebaseerd waren. Op deze manier werd de mysterieuze variabiliteit van de menselijke psyche, die onvermijdelijk bij deze uitspraken betrokken is, aan banden gelegd.

Het proefschrift is gebaseerd op acht artikels die aangeboden zijn ter publicatie in diverse internationale vaktijdschriften. Deze artikels zijn naar hun onderwerp gebundeld tot vier hoofdstukken (II - V).

In *Hoofdstuk I* (de Synopsis) worden eerst enkele basale begrippen en problemen met betrekking tot het enkelvoudig waarnemen met twee ogen besproken (zoals dispariteit, retinale dispariteit, diplopia, diplopia drempel en stereopsis), waarna de onderzoeksvragen worden aangegeven. Deze onderzoeksvragen betreffen de aard van de sensorische processen die ten grondslag liggen aan het enkelvoudig waarnemen met twee ogen, en de samenwerking tussen deze sensorische processen en de bijbehorende motorische processen. Na een korte bespreking van de hierbij verkregen experimentele resultaten wordt ingegaan op experimenten die gedaan zijn om een door enkele recente publikaties ontstane derde probleemstelling op te lossen, te weten, de wijze waarop het enkelvoudig waarnemen met twee ogen onder veeleisende omstandigheden tot stand komt. Het geheel wordt afgesloten met samenvattende konklusies gevolgd door enkele slotopmerkingen over de oorsprong van het onderzoek en over de diverse probeersels en beproevingen

In *Hoofdstuk II* wordt ingegaan op een onopgelost geschilpunt in de literatuur bij de start van het onderzoek. Dit geschilpunt betrof de *aard* van de sensorische processen die ten grondslag liggen aan het enkelvoudig waarnemen met twee ogen. Een belangrijke, bijna traditionele opvatting is dat deze sensorische processen een fusiemechanisme zijn dat de verschillen tussen de beelden op de netvliezen van de twee ogen (de *"retinale" dispariteiten*) elimineert. Volgens het hiertegen opponerende gezichtspunt bestaat er niet zoiets als een fusiemechanisme.

In dit kader zijn *drie* deelonderzoeken uitgevoerd. In het *eerste* deelonderzoek zijn de grootte en aard onderzocht van de dubbelbeeld drempel die aangeeft vanaf welke retinale dispariteit niet meer enkelvoudig wordt waargenomen met twee ogen. In het *tweede* deelonderzoek is het effect van de presentatie tijd van de stimulus op de detectie en dubbelbeeld drempels voor verticale dispariteiten onderzocht teneinde na te gaan of het verwerkingsmechanisme de dispariteiten elimineert dan wel onthult. In het *derde* deelonderzoek is de detecteerbaarheid van verschillen tussen twee verschillende verticale dispariteiten bepaald als functie van de referentie dispariteit teneinde na te gaan of deze detecteerbaarheid rondom de nuldispariteit (waar enkelvoudig wordt waargenomen) zó veel slechter is dan bij relatief grote referentie dispariteiten (waarbij dubbelbeelden worden gezien) dat aangenomen moet worden dat er rondom de nuldispariteit een *speciaal* mechanisme werkzaam is dat dispariteiten *elimineert*.

De in deze drie deelonderzoeken verkregen resultaten bleken het standpunt te staven dat het visuele systeem geen sensorisch fusie mechanisme herbergt. Het enkelvoudig waarnemen met twee ogen ondanks de aanwezigheid van retinale dispariteiten lijkt het gevolg te zijn van het (functionele) tekort schieten van een sensorisch detectie proces dat erop uit is de aanwezigheid van retinale dispariteiten te onthullen. Dit tekort schieten moet toegeschreven worden aan de neiging die bij proefpersonen bestaat om tolerante beoordelingskriteria te hanteren, aan de beperkte nauwkeurigheid en reproduceerbaarheid waarmee dispariteitsinformatie over beeldverdubbeling verwerkt wordt en aan verlies van informatie over het teken van dispariteit. Dit laatste geeft uitdrukking aan het feit dat positieve en negatieve dispariteiten (bijvoorbeeld het beeld van de stimulus in het linker oog omhoog en in het rechter oog omlaag verschoven ten opzichte van de corresponderende lokaties in de twee ogen, en vice-versa) dezelfde mate van waargenomen verdubbeling geven.

In *Hoofdstuk III* worden *twee* deelonderzoeken gepresenteerd die betrekking hebben op een belangrijk aspect van het enkelvoudig waarnemen met twee ogen dat nog niet echt eerder was onderzocht. Dit aspect betreft de samenwerking tussen enerzijds de vergentie bewegingen van de ogen die retinale dispariteiten minimaliseren door de ogen uit te richten en anderzijds de processen die ten grondslag liggen aan sensorische tolerantie voor deze dispariteiten.

In het *eerste* deelonderzoek is de grootte van foveale dubbelbeeld drempels vergeleken met de grootte van de "fixatie" dispariteiten die spontaan optreden bij continue fixatie als gevolg van onnauwkeurigheid in de (motorische) uitrichting van de ogen. Bovendien is de spreiding van deze foveale dubbelbeeld drempels vergeleken met de spreiding van de fixatie dispariteiten. In het *tweede* deelonderzoek zijn de grootste verticale (retinale) dispariteiten (op eccentriciteiten van 0.5 tot 4 booggraden in het gezichtsveld) die nog geen beeldverdubbeling geven vergeleken met de corresponderende kleinste verticale (retinale) dispariteiten die vergentie bewegingen van de ogen kunnen initiëren. In beide deelonderzoeken is een subjectieve nonius-lijn methode gebruikt om informatie te verkrijgen over de uitrichting van de ogen (vgl. Hoofdstuk V).

Een opmerkelijke vondst was dat vergentie bewegingen van de ogen opgewekt kunnen worden door verticale dispariteiten die zo klein zijn als de afstand tussen de middens van aangrenzende receptoren in het netvlies.

De verkregen resultaten suggereren dat de grondslag van de samenwerking tussen motorische en sensorische processen die ten grondslag liggen aan het enkelvoudig waarnemen met twee ogen is, dat het motorische systeem dat de vergentie bewegingen in reactie op retinale dispariteiten stuurt gevoeliger en nauwkeuriger is dan het sensorische systeem waarmee de psychofysische beoordeling van deze dispariteiten in termen van beeldverdubbeling tot stand komt. Retinale dispariteiten, vooral die rondom het fixatiepunt, worden dus voortdurend motorisch weggewerkt door vergentie bewegingen van de ogen met een nauwkeurigheid die meer dan voldoende is.

In *Hoofdstuk IV* wordt ingegaan op enkelzien met twee ogen onder veeleisende omstandigheden.

Toen het onderzoek voor dit proefschrift bijna beëindigd was verschenen er enkele publikaties waarin gesuggereerd werd dat tijdens twee specifieke veeleisende omstandigheden de (motorische) uitrichting van de twee ogen op een visuele stimulus verrassend veel zou verslechteren. Omdat nog steeds enkelvoudig zou worden waargenomen met twee ogen zou de sensorische tolerantie voor retinale dispariteiten aanzienlijk groter moeten zijn geworden (ongeveer een factor 10).

In de ene situatie kreeg de proefpersoon de opdracht zo goed mogelijk met beide ogen naar een bepaalde stimulus te blijven kijken terwijl ondertussen het hoofd in de horizontale richting heen en weer bewogen moest worden. In de andere situatie werd de proefpersoon geconfronteerd met een stimulus die voor het linker oog veel hoger stond (tot 6 booggraden) dan voor het rechter oog (of vice versa).

De bovengenoemde experimenten zijn herhaald in *twee* deelonderzoeken waarbij de uitrichting van de ogen gemeten is met een speciaal ontworpen nabeeld methode in plaats van met de objectieve methode die in de bovengenoemde gepubliceerde onderzoeken gebruikt is en waarbij de richtingen van de visuele assen van de twee ogen gemeten worden met behulp van speciale, op de ogen vastgezogen kontaktlenzen.

De uitrichting van de ogen op de stimulus bleek onder de veeleisende omstandigheden een factor 10 beter te blijven dan in de voorgaande studies gerapporteerd was.

In *Hoofdstuk V* wordt ingegaan op de geldigheid van de subjectieve nonius-lijn methode, die veel gebruikt wordt om nauwkeurige informatie te verkrijgen over de (motorische) uitrichting van de ogen. Deze nonius-lijn methode is bij de experimenten beschreven in hoofdstuk III toegepast.

Bij de subjectieve nonius-lijn methode wordt verondersteld dat de *waargenomen* relatieve verschuiving van twee onderling gescheiden maar *fysisch* uitgelijnde nonius lijnen, die ieder afzonderlijk met slechts één oog gezien kunnen worden, gelijk is aan de mate waarin de ogen niet uitgericht zijn.

In *één* deelonderzoek zijn subjectief verkregen gegevens over de verticale uitrichting van de ogen vergeleken met objectieve registratie van deze uitrichting onder de specifieke stimulus condities waarbij de subjectieve nonius-lijn methode in het onderzoek voor dit proefschrift gebruikt is.

De verkregen resultaten duiden erop dat de subjectieve nonius-lijn methode voor de bepaling van de uitrichting van de ogen in de verticale richting geldig is, evenals de resultaten van eerdere studies erop duiden dat deze methode geldig is voor de bepaling van de horizontale en torsionale uitrichting.

CURRICULUM VITAE

De schrijver van dit proefschrift werd geboren op 22 juni 1953 te Makassar in Indonesië. In 1970 behaalde hij het diploma HBS-B aan de Christelijke Scholengemeenschap te Voorburg (Z.H.). Van 1970 t/m 1975 studeerde hij technische natuurkunde aan de Technische Hogeschool te Delft. In de afstudeerfase werden twee onderzoeken gedaan. In het eerste onderzoek is de bruikbaarheid van de "contrast evoked potential" voor objectieve perimetrie (gezichtsveld onderzoek) nagegaan. In het tweede onderzoek zijn in elektrofysiologische experimenten de spatiële sommatie eigenschappen van ganglioncellen in het geïsoleerde netvlies van de goudvis onderzocht. Beide onderzoeken zijn uitgevoerd op het Laboratorium voor Medische Fysica van de Universiteit van Amsterdam onder leiding van Prof. Dr. Ir. H. Spekreijse, waarbij Prof. Dr. G. van den Brink als mentor van de TH Delft optrad. Na het behalen van het ingenieursexamen in januari 1976 heeft hij ruim twee jaar als wetenschappelijk medewerker gewerkt op zowel het Laboratorium voor Medische Fysica te Amsterdam (via de Gezondheidsorganisatie TNO) als op het Interuniversitair Oogheelkundig Instituut te Amsterdam onder leiding van Prof. Dr. L.H. van der Tweel en Prof. Dr. Ir. H. Spekreijse. In deze periode is voornamelijk toegepast visueel onderzoek bij Multiple Sclerose patienten gedaan. Het betrof hier een evaluatie van de "visual evoked potential" als diagnose middel en het verrichten van "uitsteltijd" perimetrie. Daarnaast is de "contrast evoked potential" in een systeem-analytische benadering met behulp van temporele amplitude - en frequentiemodulatie onderzocht. Vanaf april 1978 is hij als wetenschappelijk onderzoeker via de Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek (Z.W.O.) en de Nederlandse Stichting voor Psychonomie onder leiding van Prof. Dr. G. van den Brink werkzaam op de afdeling Biologische en Medische Natuurkunde van de Erasmus Universiteit Rotterdam, waarbij aan het in dit proefschrift beschreven onderzoek gewerkt is.