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Foveal diplopia thresholds and fixation disparities

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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: the accuracy of alignment in the vertical direction (within 1-2 min) is remarkably good and much better than in the horizontal direction; the largest disparities occurring due to restricted alignment accuracy are usually substantially smaller than the foveal diplopia thresholds; interindividual variability in the magnitude of foveal diplopia thresholds is not due only to interindividual variability in the alignment accuracy; and 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.

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 that the images in the foveae of the two eyes fall on nearly corresponding retinal locations. However, ocular alignment is not perfect, and this results in residual disparities 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 and 8 min[1] (Riggs & Ratliff, 1951, SD $<$ 1 min; Ditchburn & Ginsborg, 1953, and Krauskopf, Cornsweet, & Riggs, 1960, SD = 1.9–2.5 min; Fender & Julesz, 1967, SD = 7-8 min). 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 min (2-3 times SD) in different studies.

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

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

In the literature, data of this kind have been gathered with only a rather restricted accuracy for one subject, the quantity measured being 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 concerning the comparative magnitudes of fixation disparities during steady binocular fixation and foveal diplopia thresholds for both horizontal and vertical disparities will be provided and analyzed. 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, & Prangen, 1949; Ogle & Prangen, 1953).

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METHODS

Stimulator

The stimuli were presented in an electronic stereoscope consisting of a white background screen (diameter 15 deg, mean lu-

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minance level 3 cd/m^2) and two XYZ displays (the preliminary experiments, the results of which are presented in Figure 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 units above the (contrast) threshold for perception of the stimulus. The line widths of the stimuli were .3 mm (1.0 min) for the Philips oscilloscopes and .35 mm (1.2 min) for the HP 1321A displays. When the beam splitters were looked through with a telescope (magnification 30), the angular dimensions of the images on the two displays were equalized to within .3 min. 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 .1 min 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 center of a continuously visible fixation circle with a diameter of 1 deg. In addition, the orientation of the disparity was marked on the background screen with a black line interrupted in the central 1.5 deg, where the stimuli on the display screens were presented.[2]

Test stimuli. The test stimuli for the determination of *fixation disparities* (Figures 1A and 1B) consisted of a pair of lines 15 min long and 1 min wide. 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 (Figure 1A). The monocular nonius lines (Figure 1A, bottom) had a horizontal separation of 6 min between the endpoints. The uncrossed horizontal disparity between the dichoptic nonius lines (Figure 1A, top) was adjusted by the subjects in order to obtain a perceived horizontal separation of 6 min 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 deg (Figure 1B).

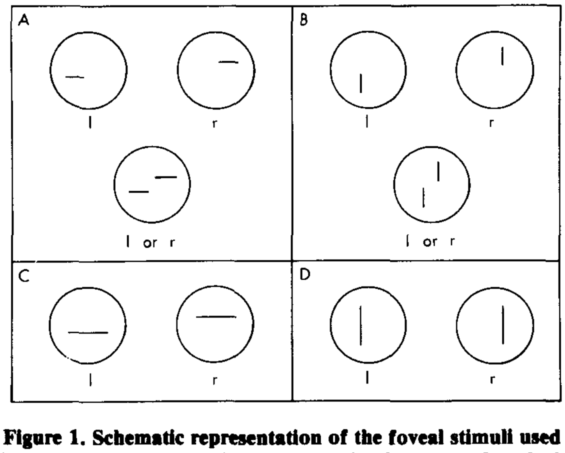

Figure 1. Schematic representation of the foveal stimuli used in this study. The letters l and r stand for stimuli presented to the left and right eye, respectively.

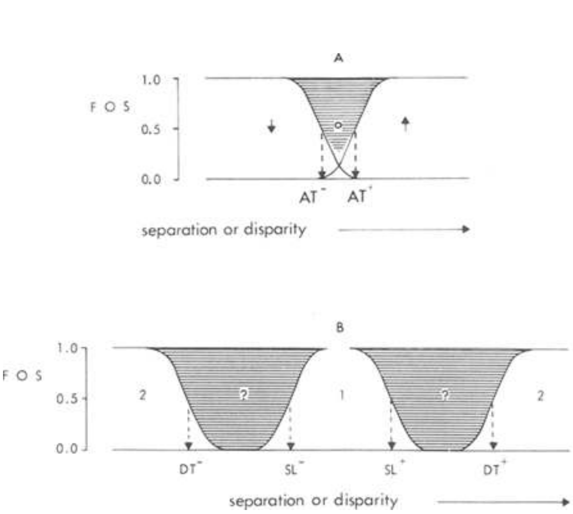

Figure 2. (A) Classification of fixation disparity assessments. Schematic representation of the frequency of seeing (FOS) negative displacement (↓) and positive displacement (↑) between a pair of nonius lines as a function of the separation or disparity level in a classification procedure, with no displacement (0) as the third possible category. (B) 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 (?).

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 endpoints 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 30 min long and 1 min wide. The thresholds for vertical disparity were determined with horizontal test lines (Figure 1C), and the thresholds for horizontal disparity with vertical test lines (Figure 1D).

Classification of Fixation Disparity Assessments (see Figure 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 the two nonius lines were in line (no displacement, 0). 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, 0). The no-displacement classification was used to avoid a possible bias resulting from an asymmetrical classification of doubtful displacements, and to avoid confusion of the effects of a rise in the threshold and in the noise level (see Alignment data in Results and Discussion). The frequencies of seeing these three percepts ("FOS" values) were determined as a function of the physically induced displacements, with 40-80 trials at each displacement value. In contrast to typical practice in the assessment of vernier acuity using a two-alternative forced-choice procedure, the subjects were not forced to use the sharpest possible criterion for positive displacement or negative displacement.

Classification of Diplopia Threshold Assessments (see Figure 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 and not restless or 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 three 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 three hypothetical disparity ranges, in each of which one of the three possible percepts (1, ?, or 2, see Figure 2B, or ↓, 0, or ↑, see Figure 2A) is always seen. Each (abrupt) transition between neighboring 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. As indicated in Figure 2, the above-mentioned convolution simply results in an integrated Gaussian distribution function (see the FOS curves for ↓, ↑, 1, ?, and 2 in Figure 2) unless the separation between neighboring transitions is small in comparison with the amount of noise (see the FOS curves for 0, indicated by the boundary of the shaded area in Figure 2A and for 1 in Figure 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 the lower and upper limits of "the" diplopia thresholds, 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 (see: The distribution of fixation disparities).

Experimental Procedure

The data were collected in sessions of 240 trials each. Each session lasted about 30-45 min with a rest period of at least 15 min 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 .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 sec.

Subjects

The data were obtained from three subjects (A.L.D., B.d.L., and A.E.H.P.) who had previously participated in a number of similar experiments.

The distribution of vertical fixation disparities and the vertical disparity thresholds were determined in Subjects A.L.D., B.d.L., and A.E.H.P. For the determination of the distribution of horizontal fixation disparities, only Subjects A.L.D. and B.d.L. participated, because subject A.E.H.P. was no longer available. All subjects were corrected for myopia (−.75 D for both eyes for A.L.D., −3.25 D left eye and −3.00 D right eye for B.d.L., and −4.75 D for both eyes for Subject A.E.H.P.). In addition, Subject A.E.H.P. 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 diopter 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.

RESULTS AND DISCUSSION

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 Figures 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, for example, 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, but we did test the method in a simple psychophysical experiment in which the subject (A.L.D.) looked at the portion of a vertical, 10-deg-long fixation line between two dichoptic, 20-min-long nonius lines with a randomly chosen vertical disparity. The nonius lines were positioned at the centers of the vertical fixation line and two squares (of sides 1 or 8 deg), the two squares being presented dichoptically with a certain amount of vertical disparity (see Figure 3A). The subject was asked to adjust the vertical disparity in the nonius lines to optimally align them. The whole stimulus was then removed and then re-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 min between the squares.

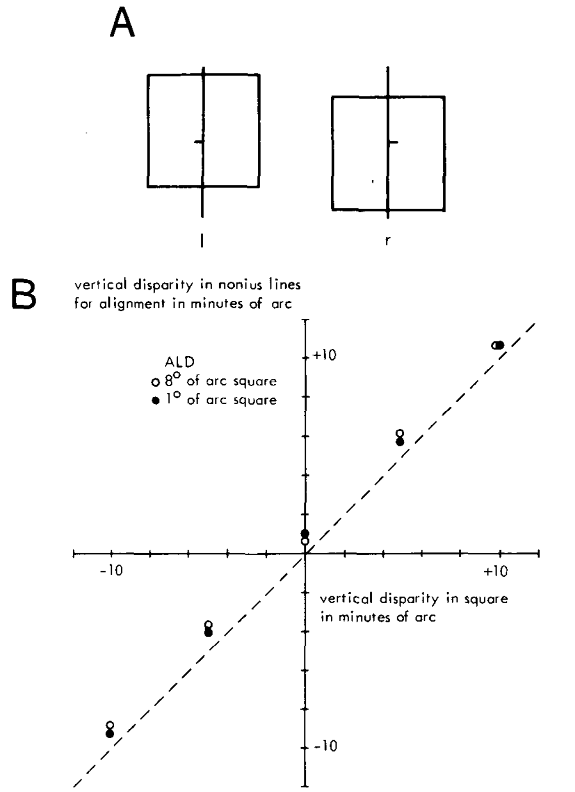

Figure 3. (A) Schematic representation of the line stimuli used to obtain the data of Figure 3B. The letters l and r stand for presentation to the left and right eye, respectively. (B) Test of validity of subjective alignment method for determination of fixation disparity. Vertical disparity to be introduced 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.

The mean values of the adjusted vertical disparities between the nonius lines are plotted in Figure 3B as a function of the vertical disparity between squares with 1-deg (solid circles) and 8-deg (open circles) sides.

Inspection of Figure 3B shows that, apart from an offset of about .9 min, the vertical displacement induced between the dichoptic nonius lines is equal to the vertical disparity between squares with sides of 1 and even 8 deg. It is highly unlikely that the displacement induced in the nonius lines is due to a sensory process, since this would require interaction between the square and the otherwise uncorrelated nonius lines over distances in the visual field up to at least 4 deg with an accuracy of at least 1 min. 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 been reported previously, for example, by 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 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 .2 sec and certainly not before .1 sec (Westheimer & Mitchell, 1956).

A presentation time of 200 msec is, however, not short enough to "freeze" the eye movements, that is, to prevent displacements of the images of the test stimulus on the retinas 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; that is, the effects of particular interest to us are completely eliminated under these conditions (Woo, 1974; Woo & Reading, 1978). This is confirmed by the results of some of our own experiments using presentation times of 20 msec (see Figure 6 and Table 2). The singleness limit for vertical disparity between dichoptic test lines (stimulus of Figure 1C) then amounts to 1.4 min (SD = 1.6 min), which is equal to the singleness limit for vertical separation between monocular test lines (stimulus of Figure 1C, but with both horizontal lines presented to one eye), which amounts to 1.4 min (SD = .5 min). The dichoptic data just contain more noise.

With a stimulus presentation time of 200 msec when the involuntary eye movements are not frozen, there will be some variation of the fixation disparity due to involuntary eye movements. This variation was found to be so small that the subjects did not notice it, either during determination of diplopia thresholds or during 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.

Diplopia Thresholds and Fixation Disparities

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

The frequency of seeing unequivocal singleness is shown for Subjects A.L.D., B.d.L., and A.E.H.P. in Figure 4 as a function of the vertical disparity (open circles) for the 200-msec presentation of the horizontal test lines shown in Figure 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 Figure 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 ½(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 which the perceived alignment is optimum; AT+ and AT− are the positive and negative alignment thresholds defined in Figure 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−, so it lies halfway between these two vertical bars in the graph. The disparity values at which the shifted FOS curves for upward and downward displacements reach the values of 0 and 1 define approximately the range of the vertical fixation disparity.

The frequency of seeing unequivocal doubleness for Subject A.L.D. and the frequency of seeing unequivocal singleness for Subject B.d.L. are shown in Figure 5 as functions of the horizontal disparity (open circles) for 200-msec presentation of the vertical test lines shown in Figure 1D. In Subject B.d.L., 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 Figure 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 Figure 4).

The major conclusions to be drawn from Figures

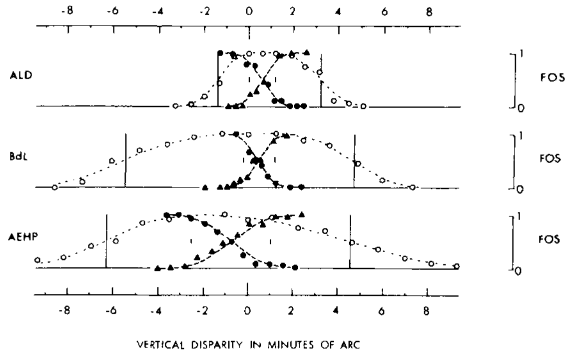

Figure 4. Comparison of data on vertical fixation disparities (solid symbols) and diplopia thresholds (open circles) obtained from three subjects (A.L.D., B.d.L., A.E.H.P.) for 200-msec presentation of the horizontal nonius lines shown in the upper part of Figure 1A and the horizontal test lines shown in Figure 1C, respectively.

Table 1
Alignment Data (in Minutes of Arc) for Horizontal Test Lines With Vertical Separation or Disparity and for Vertical Test Lines With Horizontal Separation or Disparity

	(A) Horizontal Test Lines						(B) Vertical Test Lines					
Subject	AT/D	SD/D	AT/M	SD/M	F*	SD/F	AT/D	SD/D	AT/M	SD/M	F**	SD/F
A.L.D.	.6	.6	.4	.25	+.5	.5	.7	1.6	.5	.35	+5.0	1.6
B.d.L.	.7	.6	.4	.3	+.4	.5	1.1	1.7	.4	.3	+7.4	1.7
A.E.H.P.	1.6	1.2	.6	.30	−.7	1.2						
A.L.D., 20 msec	.5	.7	.5	.25	+.6	.65	.9	1.6	.5	.3	+5.6	1.6

*Note—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]½ = standard deviation of the distribution of fixation disparities. *"+" = right eye points to a higher position than left eye; "−" = right eye points to a lower position than left eye. **"+" = eyes' convergence is "behind" the fixation stimulus.*

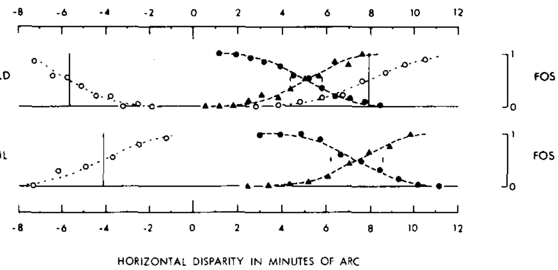

Figure 5. Comparison of data on horizontal fixation disparities (solid symbols) and diplopia thresholds (open circles) obtained from two subjects (A.L.D. and B.d.L.) for 200-msec presentation of the vertical nonius lines shown in the upper part of Figure 1B and the horizontal test lines shown in Figure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

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, since this was done in a previous paper (Duwaer & 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, that is, 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 that is not present in the processing of displacements between monocular nonius lines. The advantage of the classification used in this study, with "undetermined displacement" as a third category in addition to "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 have been the case if the subject was forced to use one of only 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, that is, 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 .4-.7 min in the vertical direction and 5-7.4 min 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, that is, the standard deviation that would have been obtained had the eyes remained perfectly aligned. The standard deviation of the monocular alignment threshold (SD/M) is taken as a measure of this intrinsic inaccuracy.[6] The correction is 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:

$$(SD/D)^2 = (SD/F)^2 + (SD/M)^2$$

or

$$SD/F = [(SD/D)^2 - (SD/M)^2]^{1/2}.$$

The results of this calculation are given in Table 1. Inspection of this table shows that SD/F for vertical disparities amounts to .5 min in Subjects A.L.D. and B.d.L. and to 1.2 min in Subject A.E.H.P. SD/F for horizontal disparities amounts to 1.6 min in Subject A.L.D. and 1.7 min in Subject B.d.L.

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 A.L.D. with 20-msec presentation time (see Table 1 and Figure 6). The standard deviation for horizontal fixation disparities remained

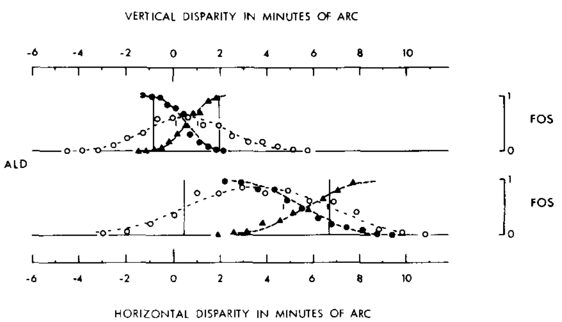

Figure 6. Comparison of data on fixation disparities and diplopia thresholds in the vertical direction (top) and in the horizontal direction (bottom) obtained from Subject A.L.D. for 20-msec presentation of the nonius and test lines. For further details, see captions for Figures 4 and 5.

at 1.6 min, while that for vertical fixation disparities increased from .5 to .65 min.

It is concluded that *the accuracy of the vertical alignment of the eyes is remarkably good, and much better than the accuracy of horizontal alignment.* This can be understood if it is recalled that horizontal alignment can be influenced by voluntary control and the accommodation-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 fixation disparity (F) and the *lowest* thresholds marking a transition to deteriorated singleness, that is, what is defined as the onset of image doubling 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 threshold 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 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 A.L.D. to 8.6-11.8 in Subject B.d.L., and to 4.5-4.8 in Subject A.E.H.P. Nevertheless, these diplopia thresholds do show critical adaptation to the overall amount of intrinsic noise present, as is shown by the fact that these thresholds, expressed in terms of their own standard deviations, amount to 2.9 for Subject A.L.D., 3.0 for Subject B.d.L., and 2.2 for Subject A.E.H.P. 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 A.L.D. and 6.8-9.2 in Subject B.d.L.

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 .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 .2 sec (Duwaer & 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 B.d.L. and A.E.H.P. are larger than those of Subject A.L.D., while only the fixation disparities of Subject A.E.H.P. are larger than those of Subject A.L.D. 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 (.5-.6 min, see Table 2) are much smaller than those of the horizontal fixation disparity (1.6-1.7 min, 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, however, is hardly surprising when we remember that fixation disparities do not introduce *relative* disparity which could interfere with 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, that is, 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 .6 min for vertical disparities and 1.0 min for horizontal disparities in Subject A.L.D., 1.2 min for vertical disparities and 2.0 min for horizontal disparities in Subject B.d.L., and 2.0 min for vertical disparities in Subject A.E.H.P.

The results obtained in Subject A.L.D. with presentation times of 20 msec show that the foveal sensory noise increases when the presentation time of the test stimulus is reduced. As shown in a previous study (Duwaer & van den Brink, 1981), the sensory noise also increases outside the fovea.

Table 2
Thresholds With Standard Deviations for Vertical and Horizontal Disparity (in Minutes of Arc)

	(A) Vertical Disparity*										(B) Horizontal Disparity**									
Subject	SL+	SD	T	DT+	SD	SL−	SD	T	DT−	SD	SL+	SD	T	DT+	SD	SL−	SD	T	DT−	SD
A.L.D.	3.2	.9	1	5.0	.9	−1.4	.7	1	−2.9	.7	1.0	.5†	2a	7.8	2.2	−1.0	.5	2b	− 5.7	1.6
B.d.L.	4.7	1.4	1	9.5	.8	−5.5	2.0	1	−9.9	1.1	.9	.6	2a	23.0	3.3	−4.1	2.0	1	−13.0	2.4
A.E.H.P.	4.6	3.1	2	7.1	1.8	−6.3	1.9	2	−8.1	2.3										
A.L.D., 20 msec	2.0	1.6	1	4.8	1.4	− .8	1.6	1	−3.1	1.6	6.7	2.1	1	11.0	2.1	+ .5	2.1	1	− 2.9	2.5

Note—*SL = singleness limit; T = transitional percept between SL and DT; DT = doublness 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, unsharpness, restlessness; 2 = subject not able to specify the percept.* **"+" = *uncrossed horizontal disparity (equivalent to test line "behind" the fixation stimulus);* "−" = *crossed horizontal disparity. Transitional percepts (T): 1 = broadening, unsharpness, restlessness; 2a = unequivocal singleness, image apparently behind fixation stimulus; 2b = unequivocal singleness, image apparently in front of fixation stimulus.* †*After a training period, Subject A.L.D. virtually lost the percept "no depth," so that only the percepts "in front" or "behind" remained. A two-alternative forced-choice procedure showed that this subject could then detect a disparity of .2 min of arc 50% correctly.*

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

Apart from the above-mentioned introduction of noise, the most prominent transformation of the physical stimulus during its passage to the retinal stimulus is the addition of an overall mean horizontal disparity shift of 5-7.3 min. 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 be affected effectively only by horizontal disparity near the endpoints. 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 produced only by a nonzero 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 A.L.D. (see Figure 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, because the asymmetry also occurred at 20-msec presentation times when relative depth was only rarely perceived (see Figure 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 & van den Brink, 1981).

CONCLUSIONS

(1) 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.

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

(3) 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.

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NOTES

1. In this paper, all angular measures will be expressed simply in degrees (deg) or minutes (min) without the qualification "of arc" each time.

2. For the determination of vertical fixation disparities in Subject B.d.L., the line on the background screen had to be extended to the center 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 min) 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 A.L.D. 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 endpoints of dichoptically presented nonius lines due to varying fixation disparities can be ignored. 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 min. In this range, which is about equal to the range of effective separations due to horizontal fixation disparities, the relevant data do not deviate by more than 10% in Subject A.L.D. and 25% in Subject A.E.H.P. from the data for a separation of 6 min.

4. With the usual assumption of Gaussian distribution functions, we can calculate the equivalent vernier acuity that would result in a false alarm rate that was the same at the displacement AT/M as that determined by AT/M ± SD/M. These equivalent vernier acuities amount to .15-.25 min, or 10-15 sec. These values are comparable with those reported for stimuli on XYZ displays by other authors (e.g., Westheimer & 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 A.L.D., for instance, the mean horizontal fixation disparity then amounted to +1 min (and the standard deviation of the fixation disparity to 1.4 min).

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.

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