Constraints in Traditional Analyses of Stereopsis

Stereoscopic depth perception has been analysed in numerous laboratory experiments since Wheatstone’s (1838) discovery that disparity is a sufficient and compelling stimulus for the perception of depth. One of the amazing properties of stereopsis is its extremely low disparity threshold (stereoscopic thresholds are on the order of 10\(^{-5}\); e.g. Westheimer, 1979a). This qualifies stereoaucity as an example of hyperacuity; i.e., discriminable retinal distances are smaller than the inter-receptor distances in the fovea and the sizes of receptive fields of individual cortical neurons (Westheimer, 1979b). While such performance is remarkable enough in monocular forms of hyperacuity, such as the detection of vernier offset, stereoaucity has to cope with the additional problem that angular distances in the image on two different retinas have to be compared.

This raises the question of whether stereoaucity is in any way limited by the precision of oculomotor control, and in particular by the control of vergence. Classical studies of stereopsis have avoided this problem by minimizing eye movements, rather than dealing with it explicitly. Eye movements have been minimized in two ways.

Firstly, head movements, a major natural source of gaze instability, have been usually avoided by supporting or fixing the subject’s head with chin rests or bite-halos. Needless to say, the more effective this procedure is, the less representative the experimental situation becomes with respect to the natural behavioral conditions in which stereopsis evolved.

Secondly, ocular vergence has usually been constrained to a fixation plane or a fixation point by providing each of the subject’s eyes with the same visual frame of reference or fixation target. The effectiveness of such constraints on fixation has almost never been assessed by objective eye movement recordings, although subjective estimation of vergence accuracy by means of a nomius line procedure has been used in a number of studies (e.g. Regan and Beverley, 1973a,b).

Fixation points or other visual frames have effects that go beyond their control of vergence. These points and frames become part of the visual stimulus configuration where they can serve as a visual reference. Sometimes this situation is created intentionally, and the fixation mark is, in effect, one target in a stereogram, relative to which the depth of a second target is judged (e.g. Richards, 1970, 1971). In other experiments, the fixation marks are shown only intermittently, and replaced for brief periods by the complete stereogram in which depth must be discriminated (e.g. Westheimer, 1979a). Alternatively, a fixation mark has been replaced intermittently by a single target, the depth of which had to be judged relative to some fixation mark which was not seen at the same time (JONES, 1977). In many other cases, stereo-targets and fixation marks or other visual frames have been presented simultaneously while the investigators were apparently unaware of the complications created by their addition to the experimental configuration.

This is a crucial point because it means that, in the past, absolute and relative disparities have often been confused in the laboratory. The distinction between these variables is fundamental to the understanding of binocular visual processing, and this distinction is also required to understand how stereopsis can function outside of the laboratory. This point will be elaborated in the next section.
Absolute and Relative Disparities

Disparity is illustrated in Fig. 7.1(a) for the simple symmetrical case, in which targets and fixation point are all located in the median plane. The eyes are converged on P, the binocular point of fixation. Ocular vergence ($\gamma_d$) is equal to the angle between the visual axes. The targets A and B have binocular parallaxes $\gamma_A$ and $\gamma_B$, the angles subtended by the nodal points of the two eyes at A and B.

The absolute disparities $\delta_A$ and $\delta_B$ of A and B are:

$$\delta_A = \gamma_A - \gamma_d \quad \text{and} \quad \delta_B = \gamma_B - \gamma_d$$

Thus, the absolute disparity of a target is equal to the difference between its binocular parallaxes and the ocular vergence angle. For targets closer than the fixation point the disparity is positive and usually called crossed; for targets farther than the fixation point disparity is negative, and usually called uncrossed. The terms crossed and uncrossed refer to the eye-image relation when A and B are seen in diplopia: for A, the left of the two images is seen by the right eye, whereas for B, the right of the pair of two images is seen by the right eye. Crossed and uncrossed images are not to be equated with projection on temporal and nasal retinal halves, as is made clear by the more general asymmetrical case sketched in Fig. 7.1(b), in which P is displaced laterally on the iso-vergence circle through P and the centres of rotation of each eye $C_1$ and $C_2$ (the locus of equal vergence angles with $\gamma_d$ unchanged), and A and B are located on either side of P. The parameters $\delta_A$ and $\delta_B$ are called absolute disparities, because they are scaled with respect to $\gamma_d$, which depends directly on the orientations of the lines of sight with the foveas as fixed reference points.

Crossed disparities evoke convergence; uncrossed disparities evoke divergence (Rashbass and Weisheiler, 1961; for a recent review see Collewijn and Erkelens, 1989). These vergence movements tend to reduce the absolute disparity of the target. No natural targets have a target vergence smaller than zero which corresponds to optical infinity; accordingly, there is no natural need for divergence greater than that required to render the lines of sight parallel and as a point of fact most subjects can overdiverge by only a few degrees, despite the fact that their conjugate eye movements can reach temporal deviations of as much as 40–50°. The geometrical relations described thus far do not, by themselves, initiate or control vergence eye movements, any more than the retinal locations of potential targets are sufficient to initiate or control other types of eye movements, such as smooth pursuit and saccades (e.g. Kowler et al., 1984). For instance, in the situation illustrated in Fig. 7.1, a decision will have to be made as to whether A or B should become the fixated target before eye movements will be made. In the real world, a multitude of targets at different distances and in different directions may be present within the visual field, all competing for visual attention. It is clear that a higher-level, cognitive operations must be involved in the decision process preceding any saccade or action. This point was recently verified experimentally far vergence by Erkelens (1989).

It is not necessary for a target to be present at P, the intersection of the lines of sight, for the decision to fixate A or B and to induce the correct vergence response. Actually, the configuration illustrated in Fig. 7.1(b) is much
simplified because it deals only with horizontal disparities. The lines of sight may also deviate vertically in a manner similar to the response in case of horizontal disparities, at least over a limited range of vertical disparities. (Krumhansl et al., 1977; Dowar and Den van Brink, 1981.)

In the configuration sketched in Fig. 7.1, the absolute disparities of A and B, \( \Delta x \) and \( \Delta y \) have been defined as \( \gamma_A - \gamma_B \) and \( \gamma_- \). These relations are valid irrespective of whether a target is actually present at P. When P is a real target, B will be seen farther away than P, and A nearer than P through the mechanism of stereopsis. A and B will be perceived as single objects (with fusion of the disparate two retinal images) as long as the absolute disparities of A and B are not too large; the range of disparities allowing fusion and stereopsis is known as Panum’s area (see Tyler, chapter 2). The points A and B have a relative disparity with respect to each other:

\[
\delta_{ab} = \gamma_A - \gamma_B = \gamma_- \gamma_+ \tag{7.2}
\]

In the latter expression, neither ocular vergence nor conjugate eye position is involved, thus relative disparity is independent of absolute retinal coordinates and independent of eye movements.

The distinction between absolute and relative disparity was clearly described by Binocular (1969). However, the importance of this distinction has generally been overlooked. Most investigators have failed to realize that the presence of fixation points or any other visual frame of reference changes the absolute disparity of any test target only to relative disparity, of the test target relative to the fixation target. The conclusions from such studies apply only to relative disparities, but they are, nevertheless, typically treated as if they applied to absolute disparities. This confusion has grave consequences for the interpretation of many experiments because absolute and relative disparities have entirely different significance for binocular visual processing.

**Stereopsis and Disparity**

All classical studies that reported very low disparity thresholds stereopsis used stimulus configurations that contained relative disparities. Typically, two targets were presented simultaneously and the subject had to discriminate their depth, that is, to indicate whether one target was farther or nearer than the other target. The lowest thresholds have been found for conventional, monocularly recognizable, and foveally presented, fine-line stereograms. Those thresholds are on the order of 10" and less (e.g. Howard, 1919; Ogle, 1964; Weisheider, 1976). The observed differences in depth were, of course, relative. No judgment of absolute distance was involved.

There is only one practical way of testing the perception of depth on the basis of absolute disparities without abandoning any judgments of absolute distance, and at the same time placing constraints on eye position. This can only be done with successive presentation, at k sf intervals, of two targets, subtending different binocular parallaxes.

Under the assumption that ocular vergence does not change during each brief presentation, these successive stimuli can be seen as to provide known differences in absolute disparity. All other visible features, which could act as a frame of reference, should be absent from the displays. The task of the subject is to indicate whether the target presented second is nearer or farther than the target presented first.

Only a few experiments have explored such successive discriminations of absolute disparities with the potential contribution of changes of vergence minimized. Foley (1976) did very careful experiments using lines presented on an oscilloscope, with the left eye and right eye stimulation separated by crossed polarizers. A binocular line was shown for 2s, and after an interval of 0-32s, a second line was shown for 100ms at a different disparity or in a different direction. A forced-choice psychophysical technique was used with the subjects receiving feedback about their performance. No fixation point was used and, presumably, no other visual frame of reference could be seen. Discrimination thresholds increased as a function of the interstimulus time interval. They were as low as 1° for intervals of 0-0.1s, and rose to 20-30° for intervals of 3.2-32s. Thresholds for direction (successful vernier discrimination) were slightly lower than for disparity discrimination. Foley (1976) interpreted these results in the context of an earlier model of Kindt and associates in which error accumulates over times as a result of both instability of vergence and loss of memory for the first target position.

Jones (1977) studied successive disparity detection and vergence responses to large steps in disparity (0.6-4.6°) created by the sudden replacement of a fixation point by a target with a given disparity. The second target was presented for 200 ms. These experiments were described as a follow-up of Richards' (1970, 1971) work on stereopsia for crossed or uncrossed disparities. There was, however, an important difference. In the experiments of Richards, a fixation point was present continuously. Thus, Richards studied discrimination of relative disparity, whereas Jones removed his fixation point and could, thereby, study absolute disparities. This difference may explain the surprisingly high proportion of stere anomalous-subjects (18 out of 30) identified in the experiments by Jones (1977). Only one third of these stereo-
anomalous subjects showed some form of anomaly in their
vergence responses, and all subjects had normal stereo-
acuity (better than 20") in a standard stereoscopic test.
Although Jones (1977) interpreted his large number of
anomalous subjects as indicating a commonly occurring,
specific defect of course stereopsis, the successive nature
of his task seems to be a more likely explanation of the poor
stereo depth-discrimination of 60% of his subjects.

The importance of the simultaneous presentation of
the two targets of which the difference in depth has to be
discriminated was demonstrated by Woeheim (1979a).
He compared stereoscopic thresholds for ordinary, simul-
taneously presented line pair stereograms with those for
successively presented lines at different absolute disper-
sities. The time interval was zero, with a single binocular
line executing a step in disparity and acting as a self-
reference. No effective comparison stimulus was available
within several degrees of visual angle. Thresholds for suc-
cessive discrimination were on the order of 1", in accor-
dence with Foley (1976); they were at least 10-fold larger
than a subject's best simultaneous stereo threshold.
Woeheim (1979a,b) was probably the first to express
clearly that good stereopsis requires the simultaneous
presence of the targets which have to be distinguished in
deepth, as well as the operation of some differentiating mech-
anism, which would extract relative disparities, indepen-
dent of eye movements.

Woeheim (1979a) concluded that, though the abso-
olute disparities \( \delta_a \) and \( \delta_b \) of targets A and B may be
independently elaborated, a mechanism exists for the op-
eration \( \delta_a - \delta_b \), and that this differential operation
makes stereopsis insensitive to a variety of naturally
occurring disturbances, including movement. His summa-
rising schema is reproduced in Fig. 7.2. In this
schema, stereopsis derives from relative disparity, exclu-
sively. It follows that depth, perceived on the basis of a
single, absolute disparity, will be very poor or even absent.
The discussion above was restricted to stationary tar-
gets and eyes. However, the conclusion drawn has impor-
tant implications for the effects of eye movements on
stereopsis. These implications will be elaborated in the
following sections.

Effects of Oculomotor Impairment on Stereopsis

A first concern is whether the normal eye movements
made during maintained fixation have any role in deter-
miming the limits of stereopsis. Thirty years ago they were
believed to serve an essential role in dynamic theories of
stereopsis, which postulated that spontaneous, miniature
fixational eye movements were needed for good stereo-
aicity (e.g. Ogle and Welt, 1958). Sherril and Krauskopf
(1967) discredited this theory by showing that stereopsis
thresholds were virtually identical under normal and
stabilized image viewing conditions. In other words, stereopsis
thresholds are neither increased nor de-
creased by the elimination of retinal image motion.

Of particular interest, in this respect, is the instability of
vergence, which can be demonstrated even during steady
fixation with the head fixed. Krauskopf et al. (1980) ana-
yzed eye movements during monocular and binocular
fixation using a scleral-contract lens recording technique in
which a beam of light is reflected from plane mirrors em-
bedded in the surface of large, tightly-fitted contact lenses.
They found that the smooth movements of the two eyes
were not correlated over short periods (2-s sample inter-
vals). Microsaccades in one eye, however, were always
accompanied by simultaneous saccades in the other eye.
The microsaccades in both eyes went in the same direction.
and had about the same size. A few years later, Fender and Julesz (1967), also using the scotcal contact lens technique, noticed the imperfect correlation of binocular eye movements in normal vision and, puzzled by the fact that this fluctuation of absolute disparity did not affect stereopsis, they proceeded to analyze this fluctuation quantitatively. They found that disjunctive drift of the order of 1° slowly introduced absolute disparities. Much larger absolute disparities were introduced by imperfect focusing of the microcassette. The probability that any saccade changed disparity by 3° or more in 40 ms was 0.57 when binocular point targets (transilluminated pinholes) were fused and the probability rose to 0.88 when a random dot pattern was fused. Some saccades produced vergence changes greater than 20°. Two years later St-Cyr and Fender (1969) confirmed the occurrence of fluctuations in vergence of at least 10° during binocular fixation (see their Fig. 7). Hebbard (1962), also using the scotcal contact lens technique, found a maximum range of vergence of about 10° over a period of 75 s during maintained binocular fixation.

The most recent data on binocular fixation were obtained with highly precise and accurate silicone annulus scleral sensor coil techniques (see a review by Steinman et al. 1982). The precision of vergence (expressed as a standard deviation) during binocular fixation with the head supported on a stationary biteblock was 5° (average of five subjects) for the composite eye movement pattern, containing both smooth and saccadic eye movements. Steady state errors, usually called fixation disparities, are known in addition to the dynamic imprecision of vergence described above. The size of these steady fixation disparities is somewhat controversial in the literature. Forced fusion techniques, using prisms and monocular lines, have strongly suggested the accumulation of vergence error as a function of the amount of vergence demanded, the eye movements, invariability, being too small (Pyle 1964; Ogles et al., 1967; Cronen and Hardwick-Jones, 1979; Schor, 1979a,b). The errors were found to increase at a low rate as long as vergence stimuli were small, and increased more rapidly as the limits of convergence and divergence were approached. These errors have been categorized as type I, II and III (Ogles et al., 1967), in which error accumulates equally fast with convergence and divergence (Type I), more rapidly with divergence (Type II), or more rapidly with convergence (Type III).

The rates of vergence error accumulation differ among subjects, and also depend on the configuration of the target. Typical disparities for a six diopeters base-out prism (requiring a convergence of about 3.4°) are about 5° for type I and II subjects, but often more than 20° for type III subjects (Schor, 1979a).

Objective recordings of deficits of vergence have been reported prior to the findings just described (Weathem and Mitchell, 1956; Tani et al., 1956; Alpern, 1973). However, these early observations have been criticized on technical grounds (sometimes by the authors themselves, who seemed not to like their own results, e.g. Tani et al., 1956). An influential early scotcal contact lens study by Rigs and Nieh (1960) is not subject to such criticisms. Rigs and Nieh discounted the occurrence of any substantial vergence errors. They stated that vergence movements over a range of 3° were accurate to about 2°. Such values are not incompatible with Weathem’s findings for fixation disparity, but of course they represent accuracy within only a very small part of the range of available vergence.

Hebbard (1962) compared subjectively measured fixation disparity with objective eye position recordings (also using the scotcal contact lens technique) and found a good agreement, he measured 0.60° ( prism-diopeter, objectively, and 0.44° ( prism-diopeter, subjectively. These measurements covered a range of 20 prism-diopeters base-in and base-out, corresponding to 11.3° convergence and divergence. Hebbard’s findings would predict a vergence error of 3° for a convergence of 5° (1.7%). This result is compatible with Rigs and Nieh’s (1960) findings and just about as good as any behaviour can be expected to be. Fixation disparity is, however, a systematic error, which increases as a function of vergence angle. Vergence errors can be expected to become larger, in absolute terms, when convergence increases more than tenfold to its maximum attainable angle. A more recent, direct comparison of objective (Shl double Parkinje image tracker) and subjective (noius lines) methods, was made under more stringent conditions than Hebbard’s (1962) by Kerstes and Lot (1988). They confirmed the existence of significant systematic fixation disparities. At the same time, their study revealed considerable problems in the use of nonius lines for the estimation of the accuracy of vergence. Objective and subjective measurements usually did not agree. It was suggested that the subjective localization of the nonius lines was affected by spatial interactions, exerted by the stimulus pattern being fused.

Recent observations in our laboratory in Rotterdam (Pohoda and Erkeslens, in preparation), made with the scleral silicone annulus sensor coil technique, confirm the accumulation of vergence error with increasing demands on convergence, ocular vergence being invariably smaller than target vergence. Typical errors were on the order of 20°-30° at 20° convergence. Once more, these values are compatible with many of the classical findings described above.

Recently, Collieij et al. (1988) described a new kind of transient vergence error that occurs in conjunction with horizontal saccades made between targets which do not require a change in vergence. In other words, binocular horizontal saccades cause systematic deviations from conjugacy. The eye moving in the temporal direction has con-
sistantly faster dynamics than the eye moving nasally. This results in a transient divergence. For a 30° binocular saccade, this transient vergence error has a maximum value of 1°-2°, and a total duration of about 300 ms.

Most natural gaze changes between real objects in a rich visual environment involve changes in vergence as well as in version. Traditional, analytical investigations of the control of vergence do not provide this kind of stimulation. Usually, simulation is limited, e.g., only absolute disparity can be an effective cue. Experiments of this kind produce descriptions of ocular vergence as a slow oculomotor response, with maximum velocities not much higher than about 30°/s (Rahimis and Wehstheimer, 1961; Erkelen, 1987). It is hard to understand how effective vergence could be achieved in everyday life with such poor dynamics. However, recent experiments, using a more natural stimulus configuration (real targets within a structured environment), have shown that natural smooth vergence eye movements are very much faster (up to about 150°/s), and natural vergence is a great extent accomplished by saccades of unequal size in each of the eyes—the smooth vergence component is secondary (Erkelen, et al., in prep- aration; see also Eriqet, 1986; 1986 for hints of how who would be aware when vergence was measured with a high bandwidth technique).

In conclusion, on the whole, binocular control of the eye position is not a rigidly stabilized head is good, but far from perfect, absolute disparities of up to a degree or more are probably common during the fixation of objects, especially when they are near. Significant errors also occur during gaze changes from one to another object. Such vergence errors, whose exact size can only be measured with objective eye movement recording methods, do not seem to perturb stereopsis.

Effects of Head Movements

The discussion in the previous section on oculomotor control was limited to conditions in which efforts were made to prevent head movements, allowing eye movements to be studied, as much as possible, in a stationary frame. In ordinary behaviour the head is unsupported and is always moving (Skavenski et al., 1979). These head movements are made both voluntarily and involuntarily. In ordinary behaviour, the head movements are uncoordinated with compensatory eye movements, which include re-fixation saccades, the vestibulo-ocular response and smooth pursuit. In the last decade, however, it has become increasingly clear that such compensation is not perfect, and it is conse- quent that, natural gaze is not precise. This lack of precision has two components: defects in the control of gaze direction for a single eye (a problem that can be investigated in monocular experiments) and defects in the coordination of the movements of the two eyes, causing errors of vergence in addition to errors in version (a problem that can only be investigated in binocular experiments).

There are various ways of looking at binocular coordination, depending on whether one adheres to the strict demarcation of eye movements into conjugate and dis- junctional components controlled by independent subsystems—the Hering (1868) tradition, or, whether one prefers to think of a single oculomotor system controlling the movements of each eye independently in response to naturally occurring visual conditions which require the eyes to move in the same or opposite directions with respect to the median plane. There are good reasons to question the traditional view. For example, compensatory eye movements, such as the vestibulo-ocular reflex, have been traditionally viewed as strictly conjugate; this is clearly an oversimplification. Firstly, such strict conjugacy would be functionally undesirable because the geometries of the ocular and the head axes of rotation in relation to each other, as well as the range of targets, require different compensatory movements by each of the eyes. This point was elaborated by Vivero et al. (1988), who showed that monkeys do actually tend to satisfy these requirements of using either conjugate (more general discussion of limitations inherent in traditional reflex approaches to oculomotor control see e.g. Steinman, 1986; Collewijn and Frens, 1981; Collewijn, 1988, 1989). Secondly, and more importantly, in the present context, it is not reasonable to expect control of compensatory eye movements to be more precise than the control of eye movement in the stationary head (discussed in previous section). Certainly, it would be most unlikely that the binocular coordination of compensatory eye movements would reach a precision on the order of seconds or even the magnitude of the stereo- acuity threshold. On the contrary, it seems more reasonable to expect that head movements would aggregate the imprecision of gaze demonstrated when the head is fixed in position.

The first objective evidence that head movements do indeed degrade gaze stability was obtained by the monocular sacadic eye movements (Skavenski et al., 1979), which compared gaze stability during fixation of a target at optical infinity while the subject's head was either supported on a headboard, or unsupported with the subject sitting or standing as still as possible. Merely getting off the head-board, without introducing any deliberate head movements, was enough to increase the instability of fixation by a factor of two to four.

Steinman and Collewijn (1989) were able to extend these observations to binocular retinal image motion during natural, active head oscillations. They found that com- pensatory eye movements were incomplete. There was considerable residual retinal image motion in each eye.
angles. The most complete data on the precision of vergence can be found in Coffewin et al. (1981a) and Steinman et al. (1982). Table 1 in the latter publication shows that the standard deviation of vergence increased from about 3° when the head was very steady while it was supported on a biteboard to about 0.5° to 1° when the head was oscillated actively or passively in the horizontal plane at frequencies between 0.33 and 1.33 Hz. The standard deviations of the positions of each of the eyes were of similar magnitude. A typical example of eye movements during voluntary head oscillation of an emmetropic, highly experienced ocularist subject is shown in Fig. 7.3.

The velocity of vergence (difference between velocities of compensatory eye movements in each of the eyes) increased as a function of head oscillation frequency from a baseline value of about 3° s⁻¹ to more than 1° s⁻¹ (Fig. 7.4). The effects of these instabilities of gaze and vergence on stereofusion and stereovision were reported by Steinman et al. (1983), 1983. A bar seen in front of or behind a structured background served as the stereovision target. Stereovision thresholds were measured while the subject sat still and during head oscillation. Relative disparities (crossed or uncrossed, presented in a random sequence) available for these tests ranged from 11.4° up to 59.6°. The results of the attempts to measure stereovision thresholds are summarized in Fig. 7.5. The available range of test stimuli was too coarse to measure a traditional threshold. Subjects correctly identified the position of the bar in the stereogram relative to the background, on more than 85% of all trials, including trials in which disparity was only 11.4°. Performance was the same regardless of whether the subject sat still or oscillated his head, and there were no reliable correlations between retinal image speed and the
likelihood of giving an incorrect response. These results showed that stereocuity (with relative disparity as the only cue) is preserved in the presence of fast and large changes in vergence. In other words, absolute disparity is not an important determinant of stereocuity threshold. Relative disparity, alone, determines the threshold.

In a second experiment, Steimann et al. (1985) tested the effect of head oscillations on the fusion of random-dot stereograms (Julesz, 1971). An easily-fused stereo pair was used. It showed a triangle, hovering in front of the background when it was fused (its relative disparity was 22.7°). Head oscillations (illustrated in Fig. 7.3) were made at increasing frequency in an attempt to break fusion of the stereogram. Fusion and perception of the figure-ground relationship was maintained, despite considerable fluctuations of vergence (i.e., absolute disparity). All efforts to break fusion were unsuccessful, even with vergence speeds reaching 8°/s. This robustness did not depend on establishing fusion prior to the onset of head movements; all subjects tested could easily and quickly establish fusion and stereopsis of the random-dot stereogram when it was presented while the head was oscillating rapidly and while absolute disparities were large and changed rapidly.

These results were replicated in related experiments by Patterson and Fox (1984), who used dynamic random-dot stereograms showing a Landolt C in front of a background. Their stereo-display had a crossed disparity of 11°. Exposure durations of the Landolt C were varied for each of the subjects (176 to 240 ms) in order to achieve a 79% correct criterion baseline discrimination performance while the head was held still. Subsequently, their four subjects actively rotated their heads at a frequency of 0.5 or 2.0 Hz. As illustrated in Fig. 7.6 (taken from Patterson and Fox, 1984) performance was virtually unaffected by these head movements, which were comparable to those used by us (Steimann and Collewijn, 1980; Steimann et al., 1982, 1983, 1985; Collewijn et al., 1984a,b, 1983) and, by inference, would be likely to be associated with similar errors of vergence. (Patterson and Fox did not record their subject's movements.) These findings of Patterson and Fox (1984) further corroborate the robustness of stereopsis in the presence of marked fluctuations of absolute disparity (and vergence), even when the psychophysical task was made comparatively difficult. To illustrate, (a) the random-dot stereograms were dynamic, i.e., they did not contain any monocularly identifiable features, whatsoever; (b) the task required not only a depth discrimination, but an orientation discrimination (the location of the gap) within one depth plane of the stereogram; (c) the stereograms were presented only for about 200 ms, giving subjects no opportunity to delay discrimination until some brief moment in the oscillation cycle when the vergence error happened to be small.

The reports of considerable imprecision of gaze under natural conditions by Steinman, Collewijn and coworkers were received with some scepticism by workers accustomed to believing that extremely precise binocular fixation provided the basis for effective binocular viewing (e.g., Stark, 1983). The only serious attempt known to us to refute our results experimentally was published by Duwaer (1982). He evaluated fixation stability (version and vergence) on the basis of the relative, subjectively measured, perceived distance between afterimages, when fixing for a short time in the target, in the absence of head oscillation. Duwaer's (1982) results indicated a smaller dispersion of gaze than we found (standard deviations 8.7° for direction and 3.6° for disparity). In the absence of a direct comparison of afterimage results with objective eye position recordings, we can only speculate about whether these discrepancies are real in the sense that they arise from some unnoticed artefact of the free-head scleral silicone anteros sensor coil recordings or from artifacts in the afterimage localisation technique when used to infer the position of the eyes. Fermer et al. (1987) discussed and examined potential artifacts experimentally and found that all known potential artifacts were far smaller than the imprecision of gaze we have recorded. This encourages us to believe that gaze is imprecise and our technique is not flawed. Alternatively, the perceived localisation of successively imprinted afterimages involved central visual processing, and does not, necessarily, exactly reflect eye positions or retinal coordinates (see Steinman, 1986b, p. 190) for a surprising exami-
Effects of Various Kinds of Target Motion

Imposed, Steady Absolute Disparities

Stimulus displays, which can be moved electronically while eye positions are recorded, make it possible to perform experiments concerned with the relations among absolute and relative disparities, eye movements, and stereoscopic perception.

A pioneering experiment of great importance in this context was published by Fender and Julesz (1967). They used the scotoma contact lens optical-lever technique to stabilize stereograms, whose image separation could be varied. Two types of stereograms were used: single line and random-dot stereograms. The line pair, once fused, continued to be fused as image separation was increased. Absolute, rather than relative, disparity was varied in these experiments because the retinal image of each display was stabilized on the retina. Absolute disparity was increased to about 60' when fusion was broken. Once fusion was broken, image separation had to be reduced to about 40' before the lines could be re-fused (Fig. 7.7). The result with the random-dot stereogram was similar qualitatively but very different quantitatively. Fusion was maintained as image separation was slowly increased to about 120' before fusion was broken, and, once broken, image separation had to be reduced to about 6' before the random-dot stereogram could be re-fused. This asymmetry was called hysteresis. The term refers to the persistence of fusion in the presence of larger image separations than are required to reestablish fusion once fusion has been broken. In a later study, Hyson et al. (1983) replicated the essential findings with neutral, un-stabilized vision. This was done by recording eye movements while the image separation of a random-dot target-pair was increased beyond the range of ocular divergence. Beyond this range, additional separation increases absolute disparity. They found that stereopsis and fusion were maintained for disparities up to 3' on average. They attributed this persistent fusion to a postulated process of neural remapping which occurred when such a large disparity was maintained for at least 10 s. After loss of fusion, when the maximum tolerance for disparity had been exceeded, they found a hysteresis for refusion (on average, disparity had to be reduced to 2.6').

Hyson et al. (1983) also described instances (e.g. illustrated in their Fig. 5) where even after the restoration of the image separation to the initial value, and long after fusion was regained, vergence did not return to its baseline value. Vergence had changed by as much as 2° relative to the baseline measured initially. This kind of change, if real, would constitute a second and new kind of hysteresis, for which a term such as long-term neural remapping might be appropriate. However, such a phenomenon would put an end to any presently accepted or useful definition of absolute disparity or retinal correspondence. These would be continuously adapting to new values and it is unclear how vergence could still be guided reliably towards binocular fixation in the presence of such plasticity. For the moment we prefer the more conservative explanation that such apparent remappings are caused by...
slippage of the contact lenses. These evidence to support this interpretation. Erkelens and Collewijn (1988c), repeated the experiments of Hyslop et al. (1983) with several siliconic annular sensor costs, and found that vergence always came back very close to its initial value when the half-images of a random-dot stereogram were first separated and then reunited. They were unable to confirm the long-term remapping (Fig. 7.8) with a tech-
nique known to be free from slippage artifacts. They did, however, confirm the extended Panum's area of 1 to 2', originally reported by Dineer and Julesz (1967).

More recently, Dineer and Vender (1987) published results showing that the extended range of fusion for a (stabilized) single line exists in the nasal, as well as in the temporal, direction. However, the fusalional range was smaller (on the order of 20') than in the original experiments by Dineer and Julesz (1967). As the authors suggest, this may be due to what they apparently considered to be trivial, difference in the experimental apparatus. In Dineer and Fender's (1987) experiments, the target was seen in the centre of a (stabilized) aperture with a diameter of 3'. This was probably used to maintain fixation by counteracting the strong impulse to converge the eyes when the fusalional range was tested with crossed disparities. The presence of a fixed aperture is not trivial. It is an essential detail from the conditions in the original experiment because it introduced a frame of reference which changed absolute into relative disparities. The original experiment (Fender and Julesz, 1967) was correctly titled "Extension of Panum's fusalional area in manually stabilized vision." It is important to realize that Panum's area reflects absolute and not relative disparities. This means that the Dineer and Fender (1987) experiment is not relevant to the problem studied originally and it is not surprising, therefore, that they obtained confusing results.

The distinction between absolute and relative disparity and its application to studies of Panum's area has a long, and often confused history. This issue will be elaborated in the next section. In the traditional description, noncorresponding points on the two retinas, when stimulated separately, lead to different perceived visual directions (see Chapter 1, by One). For small disparities, simultaneous stimulation of such points by the disparate images of an object leads to perception of a single object in a particular visual direction in the fused binocular scene. This state can be called single vision. If fusion does not occur, we speak of diplopia. The maximum disparity for fused vision, beyond which diplopia occurs, is conventionally represented by considering that a point on one retina corresponds to a single point on the other retina, but, rather, to a Panum's area of finite size (Panum, 1858; Oggle, 1964; Mitchell, 1964b, 1963). When defined in this way, Panum's area relates to absolute, overall disparities of the two retinal images; one of its main virtues is to allow some range of tolerance for imperfect binocular alignment. In short, Panum's area allows single vision despite instabilities and constant errors of vergence (fixation disparity). In practice, however, Panum's area is usually described as the range of disparity that allows single vision around a single fixation target. This fixation target falls near the foveal centre which means that most actual measurements of Panum's area are really estimate of the maximal relative disparity between a fixation target and some test object that allows single vision. (See Tyler chapter 7 for an extensive treatment of measurements of Panum's area defined in this way).

The great merit of the original experiments of Fender and Julesz (1967) was, that they measured the tolerance for absolute disparity. In fact, their measurements were probably the first, ever, to measure Panum's area properly. Instead, their results reflect the true Panum's area and not an extended Panum's area as they believed. Traditional determinations of Panum's area were too small because they were made in the presence of relative disparities which masked the tolerance of absolute disparities.

Note that the size of Panum's area, as determined by Fender and Julesz (1965), is consistent with the area of reobstments of stereoverison in the presence of the imprec-

## Fig. 7.8 Records of ocular vergence (solid line) and target vergence of fixator (dotted line) and background (upper dashed line) of a random-dot stereogram of which the half-images were first pulled apart and then reduced to their initial position. Fixation is signalled by the stop-dot line, sharp position: indicating borderline fusion. (Erkelens and Collewijn, 1985c).

Panum's area in manually stabilized vision. It is important to realize that Panum's area reflects absolute and not relative disparities. This means that the Dineer and Fender (1987) experiment is not relevant to the problem studied originally and it is not surprising, therefore, that they obtained confusing results.

The distinction between absolute and relative disparity and its application to studies of Panum's area has a long, and often confused history. This issue will be elaborated in the next section. In the traditional description, noncorresponding points on the two retinas, when stimulated separately, lead to different perceived visual directions (see Chapter 1, by One). For small disparities, simultaneous stimulation of such points by the disparate images of an object leads to perception of a single object in a particular visual direction in the fused binocular scene. This state can be called single vision. If fusion does not occur, we speak of diplopia. The maximum disparity for fused vision, beyond which diplopia occurs, is conventionally represented by considering that a point on one retina corresponds to a single point on the other retina, but, rather, to a Panum's area of finite size (Panum, 1858; Oggle, 1964; Mitchell, 1964b, 1963). When defined in this way, Panum's area relates to absolute, overall disparities of the two retinal images; one of its main virtues is to allow some range of tolerance for imperfect binocular alignment. In short, Panum's area allows single vision despite instabilities and constant errors of vergence (fixation disparity).

In practice, however, Panum's area is usually described as the range of disparity that allows single vision around a single fixation target. This fixation target falls near the foveal centre which means that most actual measurements of Panum's area are really estimate of the maximal relative disparity between a fixation target and some test object that allows single vision. (See Tyler chapter 7 for an extensive treatment of measurements of Panum's area defined in this way).

The great merit of the original experiments of Fender and Julesz (1967) was, that they measured the tolerance for absolute disparity. In fact, their measurements were probably the first, ever, to measure Panum's area properly. Instead, their results reflect the true Panum's area and not an extended Panum's area as they believed. Traditional determinations of Panum's area were too small because they were made in the presence of relative disparities which masked the tolerance of absolute disparities.

Note that the size of Panum's area, as determined by Fender and Julesz (1965), is consistent with the area of reobstments of stereoverison in the presence of the imprec-

## Fig. 7.8 Records of ocular vergence (solid line) and target vergence of fixator (dotted line) and background (upper dashed line) of a random-dot stereogram of which the half-images were first pulled apart and then reduced to their initial position. Fixation is signalled by the stop-dot line, sharp position: indicating borderline fusion. (Erkelens and Collewijn, 1985c).
found to be required to maintain fusion and the considerable hysteresis between the loss and reestablishment of fusion in the Fender and Julesz experiment seem not to agree with the conditions under which fusion could be maintained and reestablished when absolute disparity was changed by oscillating the head. These puzzling differences, if they represented real differences in broader context, would limit the significance of Fender and Julesz’s extension of Pavan’s area to a laboratory curiosity of little value in the coping with the dynamic instabilities of vision demonstrated in the normal vision of moving subjects.

Fortunately, there is recent evidence that the actual dynamic properties of Pavan’s area are considerably larger than apparent from the experiments of Fender, Julesz and their colleagues. Piantanida (1986) replicated the experiment of Fender and Julesz (1967), confirming that fusion of random-dot stereograms was maintained up to more than 2° of absolute disparity. At the same time, he found considerably less hysteresis. Fusion was reestablished at about two thirds of the disparity at which it had been lost. Piantanida’s results were still well outside the traditionally determined size of Pavan’s area, and similar to the hysteresis reported originally for a single line stereotarget by Fender and Julesz (1967). Piantanida attributed the differences between hysteresis in his and the prior experiment to the absence of any competing targets, i.e., he did not use the fiducial marks employed by Fender and Julesz (1967). Other words, competition between absolute and relative disparity was reduced.

Erkels et al. (1988) re-investigated hysteresis and found that its magnitude could be related to the recent history of fusion as the experiment. Only absolute disparity was studied to prevent the image-failing, usually associated with complete stabilization. Absolute disparity was slowly increased at a rate of 5°/s, comparable to the speeds of 10°/s in the experiments of Fender and colleagues. Both crossed and uncrossed disparities were varied. On average, fusion was maintained up to 4° and fusion was re-established at an absolute disparity of 8° when absolute disparity was reduced after fusion had broken. This outcome was similar to Piantanida’s (1986). However, when stereograms were abruptly presented at one or another fixed absolute disparity, without an immediately prior history of fusion at rivalry, the total range of fusion was 150°. This proves that fusion is possible at very large absolute disparities without prior fusion in a smaller Pavan’s area, and without any slow stretching of the fusion range. This result agrees well with the perceptual observations of Sterman et al. (1985), who found no difficulty in fusion a stereogram, presented during violent head oscillations (see earlier section on ocularizer imperfection and stereopsis). Erkels et al. (1988) went on to study effects of prior fusional history on measurements of Pavan’s area. He showed improved fused viewing of the stereogram for a period of 1 min, with absolute disparity set to 4°, reduced the fusional range in the same (crossed or uncrossed), but not in the opposite, direction of disparity. Uniformly-pre-exposure in the direction opposite to the subsequent test, reduced the total fusional range by an average of 1°. Uniform pre-exposure in the same-direction as subsequently tested, reduced the fusional range by an average of 48°. This reduction could account almost completely for the hysteresis effect (42° versus 8°) observed when absolute disparity is slowly increased, kept for one time beyond the limits of fusion, and then slowly reduced so as to fall, once again, within the range of fusion (see Tables 1 and 2 in Erkels, 1988). Finally, Erkels (1988) found that the zone of fusion extended somewhat further for crossed than for uncrossed disparities.

These results show that it is unlikely that hysteresis would occur when absolute disparity fluctuates during normal head movements unless the fusional range is exceeded for an extended time in a constant direction. This is a very unlikely state of affairs in an individual with a normal ocularizer system. It could occur in clinical cases of precocious fusions that might be caused by strong photic stimuli.

In summary, it seems likely that Pavan’s area is relatively wide, i.e., there is an operational zone of several degrees, within which different processes are capable of establishing fusion and extracting relative from absolute disparities, as suggested by Wuestheimer (1979a) schema (Fig. 2). Pavan’s area is functionally symmetrical in the sense that fusion can be established, as well as maintained, easily within this area. Once this is appreciated, retinal remapping need not be invoked in naturally occurring viewing conditions and hysteresis becomes a description of a reproducible phenomenon confined to particular laboratory conditions in which the fusional history of the subject is manipulated in particular way.

The results discussed above relate primarily to static disparities with very low rates of change (maximum 10°/s). In the next sections, we shall examine the effects of higher retinal image velocities.

Stereopsis of Moving Targets

The effect of retinal image motion on stereoscopic vision was investigated by Weisheimer and McKee (1978). In a prior paper, they had shown that Landolt C and vernier acuity were not adversely affected by retinal image speeds up to about 2° or 3°/s (Weisheimer and McKee, 1975). In their experiments on stereoscopic targets, the target was a line stereogram consisting of two vertical lines one above the other that was presented for 100 ms during each trial. There were four additional dots in the display outlining a square around the line stereogram. These dots were sent contin-
usually at both eyes. This square was used to define the plane of fixation and thereby establish and maintain convergence. The line targets could be moved together with respect to the fixation square. The relative disparity between the upper and lower line was varied between trials in order to measure the stereocuity threshold. In one experiment, the upper and lower lines moved sideways. Target velocities up to 2°/s had essentially no effect on the stereocuity threshold, which remained at about 10°. The result was anot only when the upper line moved and relative disparity was kept constant with respect to the lower line. In this condition any monocular cue that might have influenced the measured threshold was abolished. The view of the brief exposure time, tracking eye movements were likely to be less than 10°/sec of target speed (Kuvelier and McKee, 1987), so retinal image speed was probably similar to target speed. The results described so far show that stereocuity is not sensitive to sideways motion. In a second experiment, Weisheimer and McKee (1979a) oscillated the line stroboscope in depth to moving its right and left end half-images in opposite directions, relative to the square used to maintain fixation. In this case, stereocuity thresholds were considerably elevated with target speeds of 2°/s. This result shows that motion-in-depth was more detrimental to stereocuity than sideways motion (see also Keegan and Beverley, 1973, Fig. 2). They explained this result noting that at higher velocities of motion-in-depth, the targets were seen with disparity with respect to the fixation plane for longer periods of time. Apparently, the authors were alluding, here, to absolute disparity despite the fact that, as well as absolute disparity, was changing in their display. They proceeded with stereocuity threshold measurements in which the target line pair was stationary but was presented at different absolute disparities. Once again, the fixation plane was maintained by the continuously visible square of dots. Thresholds for the relative disparity between the two lines were found to rise rapidly when their absolute disparities placet them more than 2-3° away from the fixation plane. It is important to realize that Weisheimer and McKee's (1979a) experiments do not show that stereocuity is very sensitive to absolute disparity because relative disparity also varied in this experiment. This was true because the fixation target was continuously visible, which meant that the subject actually viewed an array of targets with two different relative disparities. 10° between the fixation square and the line targets, and less than 1° (the threshold) between the two lines. Thus, Weisheimer and McKee's (1979a) results can be interpreted as showing that the presence of a large relative disparity increases the threshold for the discrimination of a small relative disparity seen at the same time. A similar point applies to the experiments by Blakemore (1970) and Regan and Beverley (1978), who investigated the threshold for relative disparity as a function of absolute disparity, which was varied over a larger range. Since all measurements were done with the eyes fixating a continuously present target, Blakemore's (1970) findings actually also show an increased threshold for the discrimination of one relative disparity in the presence of another (larger) disparity. An effect of this kind was explicitly demonstrated in subsequent experiments by Weisheimer (1979a), who found that a standing disparity, as small as 1°, more than doubled the stereocuity threshold. Similarly, Schumer and Julesz (1984) found a systematic increase in stereothresholds as a function of the height of depth pedestals. In conclusion, there is evidence that sideways motion does not have adverse effects on stereocuity. One must bear in mind, however, that the experiments supporting this conclusion were done in the presence of a fixation frame and the effects of changes in absolute disparity on stereocuity cannot be excluded because absolute disparity was not manipulated in an independent parameter. Visible fixation frames introduce relative disparities which confound the interpretation of the results. The next section examines n-ner evidence which shows that, at least for extended targets of low spatial frequency, stereocuity is insensitive to fluctuations in absolute disparity even when absolute disparity varies by several degrees.

Stereocuity and Dynamic Changes in Absolute Disparity

Subjects have some ability to discriminate successively presented, absolute disparities, although it is clearly inferior to their ability to discriminate simultaneously presented, relative disparities (Weisheimer, 1979a). Changes of absolute disparity are effective in the control of vergence eye movements and may, therefore, be available for perception, providing, of course, that the visual system has access to the information used to control eye position. For instance, it might not be surprising to find that subjects can discriminate between crossed and uncrossed disparities, because these different stimulus configurations lead to opposite motor responses. But, even if they can make this discrimination, we are then left with the question of whether such differences in disparity are perceived as differences in depth. If this were the case, then a conspicuous change in absolute disparity should induce a visual perception of motion-in-depth.

Eriksen and Cutlerwijn (1980a,b) have shown this that is not the case. Changes of absolute disparity, alone, do not induce perceptions of motion-in-depth. Their subjects viewed a Julesz-type random-dot stereogram (size 30 x 30°), which, when fused, caused a central circular figure to be seen in front of the background. The depth difference between this figure and its background, was pro-
This result may seem in conflict with the many prior demonstrations in which changes in disparity were insufficient to induce perception of motion-in-depth (e.g., Wheatstone, 1832; Tyler, 1971; Richards, 1972; Beverley and Regan, 1973, 1975; Regan and Beverley, 1973a,b, 1979). However, in all of this prior research, motion was presented relative to a background or fixation point. In the experimental conditions of Erkelens and Collieun (1985) no frame of reference or fixation point was provided. A vivid perception of motion-in-depth was immediately induced in all subjects when a stationary reference was added to the binocular stimulus displays. When the stationary reference was small (e.g. a single bar), it was seen in motion against the stereogram which was seen as stationary. A more extended stationary reference (e.g. a grating) was seen as stationary while the stereogram, itself, appeared to move. In short, the stimulus configuration is important in the perception of induced motion-in-depth. A similar point was made for sideways motion by Dandyer (1929) who suggested that a selective principle operated in induced movement conditions, namely, surrounded objects tend to be seen as moving. Similar kinds of principles probably influence induced motion-in-depth.

In the experiments of Erkelens and Collieun (1985b) the half-images were moved sinusoidally in counterphase at frequencies between 0.25--1.5Hz and amplitudes of 0.5--2.5°, centred around an angle of 10° convergence. It was possible to correlate the motion perceived by the subject with changes in vergence, as well as with absolute disparity because the positions of both eyes and half-images were continuously recorded. Fusion and stereopsis were maintained as long as the various frequency-amplitude combinations did not reduce the velocity of the stimuli.
changes in the angle between the half-images above some maximum, which varied among the subjects from 6–3.5°. Observations made below this limit will be discussed next. As mentioned already above (Eckelens and Collewijn, 1985a) counterphase motion of the half-images at equal amplitude did not induce perceived motion. Subjects perceived a constant square-ground relationship in the stereogram and the entire fused display was perceived as stationary. Typical relationships between stereo half-images and binocular eye movements are shown in Fig. 7.9. Ocular vergence movements tended to track changes in target vergence because no fixation targets were provided. Ocular vergence tracking was not perfect, however. It was always smaller than changes of target vergence. This mismatch caused large, sinusoidal fluctuations in absolute disparity. As shown in Fig. 7.7, the maximal fluctuations of absolute disparity compatible with maintained fusion were independent of the frequency of oscillation and amounted to an area between 1–2° of crossed and uncrossed disparity (the width of this area varied among the subjects). This result is strikingly similar to the extent of Panum's area found for random-dot stereograms by Fender and Julesz (1967) in their experiments with stabilized viewing. Within the fusional zone, fluctuations of absolute disparity did not disturb stereopsis, nor did they elicit the slightest perception of motion in depth. The associated changes in vergence also did not elicit perceptions of motion-in-depth. However, these same stimuli, when combined with any apparatus or visual reference, induced very compelling perceptions of motion-in-depth (Eckelens and Collewijn, 1985a,b). These perceptions of motion-in-depth apparently require changes of relative disparity. Changes of absolute disparity do not elicit perceptions of motion-in-depth. This is clearly very different from the perception of sideways motion, which can be elicited by changes of absolute direction of the stimulus and/or associated vestibular eye movements (Eckelens and Collewijn, 1985a,b).

The observations of Eckelens and Collewijn (1985a,b) were confirmed and extended by Regan et al. (1986). One important aspect of this later investigation was the comparison of the effects of variations of disparity and extended targets on eliciting perceptions of motion-in-depth. All of their x subjects reported that there was a range of stimulus oscillations of a single dot for which clear motion-in-depth was experienced when a stationary reference (a surrounding random-dot pattern) was present, but when this reference was removed, the dot's motion immediately ceased. Thus, varying relative disparity led to perception of motion-in-depth, but varying absolute disparity did not. Threshold determinations showed that for a single dot this effect amounted to a substantial elevation of threshold (by a factor 2–7) than rather a complete abolition of stereomotion perception. Complete abolition did occur, however, when extended multi-dot targets were used; i.e. no perception of motion-in-depth occurred when only absolute, unrefereereded, changes in disparity were shown. As will be discussed later, these results could not be accounted for by the reduction of effective retinal disparities due to vergence eye movements. The finding that changes of absolute disparity elicited some weak impression of motion-in-depth of a small, unrefereereded target (in agreement with Foley, 1976 and Wosiek, 1976) has now gone at all for a multi-dot target, suggested that this difference might be caused by a lateral interaction among the dots. Regan et al. (1986) examined this possibility by varying the complexity of the stereogram displays. A multi-dot target display (diagram 2B) with randomly, but more or less evenly spaced dots (dot diameter of 0.7°) was used. A blank annulus of variable width was introduced around a central dot in the multi-dot target display. Two displays of this kind were oscil- lated in counterphase while each eye viewed one of them. Subjects directed their attention to the central dot, no stationary reference was visible. When the complete display pattern was shown, the central dot did not appear to move-in-depth for any amplitude of counterphase oscillation. The central dot also did not appear to move-in-depth when it was surrounded by a blank annulus with a radius of 0.6°. However, when the radius of the blank annulus was increased beyond 1 to 2° and oscillation amplitude was raised to 0.6° below the disparity where fusion broke down, the central dot appeared to move weakly in depth relative to the surrounding dots. (N.B. the actual positions of the central and surrounding dots were fixed; they never changed relative to one another.) In the limiting case, when only the central dot was visible, the threshold for perceiving motion-in-depth was approxi- mately the same as when it was isolated from the sur- rounding dots by a blank annulus with a 2° radius. This experiment produced evidence for a lateral inter- action among elements of a display: any apperent motion of a single target, induced by variations of absolute dispar-


