Binocular Vision with Primary Microstrabismus

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PURPOSE. Patients with primary microstrabismus have a high degree of binocularity, which suggests that their ocular misalignment may have a sensory rather than an oculomotor origin, as in large-angle strabismus. The purpose of these experiments was to determine whether microstrabismic subjects have sensory abnormalities that could give rise to a small angle of strabismus.

METHODS. The binocular disparity response functions for sensory and motor processes were compared in seven orthotropic subjects and six strabismic subjects (four with primary microstrabismus and two with infantile esotropia). Binocularity was assessed by disparity vergence (central and peripheral stimuli) and depth discrimination (relative and absolute disparities) measures. Motor and sensory disparity response functions were both determined by psychophysical methods: vergence responses by dichoptic nonius alignment and sensory responses by forced-choice depth discrimination.

RESULTS. All the strabismic subjects demonstrated normal retinal correspondence with peripheral binocular stimuli and anomalous retinal correspondence with central fusion stimuli. The microstrabismic subjects’ disparity vergence responses with peripheral fusion stimuli were centered on disparities relative to their angle of strabismus. However, with central fusion stimuli, the disparity vergence responses were relative to the subjective angle of strabismus. The microstrabismic subjects’ stereoacuities were substantially reduced, but their discrimination responses did not show an asymmetry indicative of an unrepresented population of disparity-selective mechanisms.

CONCLUSIONS. The data do not support a sensory abnormality as the primary cause of microstrabismus. The results are not compatible with an oculomotor adaptation to an inherent anomalous correspondence or with a strabismus caused by an absence of a class of disparity-selective mechanisms. Thus, just as in large-angle strabismus, the anomalous retinal correspondence and defective stereopsis of microstrabismus appear to be consequences of abnormal visual experience caused by an interocular deviation. (Invest Ophthalmol Vis Sci. 2003;44:4293–4306) DOI:10.1167/iovs.03-0346

In most forms of strabismus, a patient’s motor fusion mechanisms are anomalous or are inadequate for the maintenance of ocular alignment.1 However, in some cases in which the angle of strabismus is very small, the motor fusion amplitudes appear to be normal, whereas sensory fusion mechanisms exhibit pronounced clinical deficiencies.2–9 This form of strabismus with very small angles of deviation and relatively high degrees of binocularity has been classified as microstrabismus, which can occur as a primary or secondary condition.7 Lang7 has suggested that primary microstrabismus is essentially different from the secondary microstrabismus that is a common sequel of surgical, optical, and orthoptic treatments of large-angle strabismus. The typical characteristics of primary microstrabismus include an esodeviation of very small angle (<9 prism diopters) with harmonious anomalous retinal correspondence, mild amblyopia (often with anisometropia), foveal suppression of the deviating eye, defective stereocuity, and normal or near-normal peripheral fusion with amplitudes.4,7,8 The qualitatively normal motor fusion responses raise a question of why such patients have strabismus when their angles of strabismus are within the normal range of fusional vergence and their fusional vergence amplitudes are normal.

The paradoxical clinical findings and a high degree of binocularity may imply that primary microstrabismus is not simply a small version of infantile or acquired strabismus of larger angle. For example, it has been suggested that binocular vision is present because primary microstrabismus has a sensorial origin, as opposed to the oculomotor origin of large-angle strabismus.2,4,6 In other words, the small angle of strabismus may be an adaptation to a sensory abnormality, rather than the case with large-angle strabismus, in which the development of sensory anomalies, such as amblyopia, suppression, and anomalous correspondence, may be an adaptation to early abnormal visual experience caused by an oculomotor misalignment.1,7

A number of different sensory anomalies could cause strabismus, especially primary microstrabismus, but two seem especially important. The first suggestion of a sensorial origin for strabismus was originally proposed by Lang2 and subsequently elaborated by Kerr.5,9,10 By this model, some patients may have abnormalities in the disparity-selective mechanisms that result in an inherent anomalous retinal correspondence, with strabismus as an adaptation to the abnormal correspondence. The hypothesis of a primary sensory defect in strabismus is intriguing and, if it applies to strabismus, it seems most likely that it would occur in primary microstrabismus. A second hypothesis, based on studies of stereoanomalies11,12 and vergence anomalies13 in normal binocular vision, proposes that the sensorial origin of primary microstrabismus is a result of an innate insensitivity of disparity-selective neural mechanisms.12 In this case, a relative insensitivity of the neural mechanisms for one sign of disparity could affect both sensory and motor processes and cause defective stereocuity and abnormal interocular alignment.

The present study was undertaken to investigate the disparity-selective mechanisms of patients with primary microstrabismus, to determine whether there are abnormalities that could explain the condition. Both sensory and motor fusion mechanisms were investigated, because the interactions between these perceptual and reflexive mechanisms are closely coordinated in normal single binocular vision, and neural mechanisms should be common for the initial stages of disparity processing, although their pathways may be separate at later stages.14 Therefore, in these experiments, we studied sensory

From the College of Optometry, University of Houston, Houston, Texas.
Supported by Grants R01 EY01139, K23 EY13549, and P30 EY07551 from the National Eye Institute and by a John and Rebecca Moores Professorship from the University of Houston, Houston, Texas.
Submitted for publication April 4, 2003; revised June 26, 2003; accepted July 2, 2003.
Disclosure: R.S. Harwerth, None; P.M. Fredenburg, None.
The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked "advertisement" in accordance with 18 U.S.C. §1734 solely to indicate this fact.
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and motor responses to binocular disparity with respect to stereoscopic depth discrimination and disparity vergence responses for central and peripheral fusion. Some of the results of these studies have been presented briefly elsewhere\(^{15}\) (Harwerth RS, et al. IOVS 2001;42:ARVO Abstract 3946) and some of the data for two of the subjects with normal binocular vision (ENU and CSK) have been published,\(^{14}\) but are included in the present report for direct comparison to the data from subjects with strabisms.

**Materials and Methods**

**Subjects**

The experiments were conducted on seven subjects with orthotropic vision and six with strabismus. Although all the orthotropic subjects demonstrated normal interocular alignment by cover testing, with normal motor fusion and normal visual acuities with each eye, two of the subjects (AMS and EDR) had stereodeficiencies for reasons that have not been determined. The experimental subjects were four patients with primary microstrabismus and two with infantile esotropia. Both patients with esotropia had undergone surgical treatment during childhood, but subject JPT had residual esotropia of moderate angle and subject ADH had small-angle consecutive exotropia.

The significant clinical data of the experimental subjects’ ocular and visual characteristics are listed in Table 1. The clinical records showed that all the subjects had normal or near-normal visual acuity with each eye; however, all but one (KBH) had undergone prior patching treatment for amblyopia. The clinical examinations did not find anisometropia or eccentric fixation for any of the microstrabismic patients. The orthoptic data showed that their objective angles of strabismus were 9 prism diopters (pd) or less, and all the subjects had normal or near-normal visual acuity. Informal consent was obtained from each of the subjects and they were remunerated for their participation.

**Procedures**

The methods for the present investigations have been described in detail.\(^{14,16-19}\) In brief, the stimuli were generated on a video monitor with a computer graphics system (VSC2/3; Cambridge Research, Cambridge, UK). The independent stimuli for each eye were obtained by viewing alternate, noninterlaced frames (60 Hz) with each eye through a liquid crystal optical shutter system, which was synchronized to the monitor frame rate. The types of experimental stimuli depended on the specific investigation, with four types of disparity-dependent functions of binocular vision determined for each subject: (1) stereoacuities measured by depth discrimination for relative disparities between narrow-band Gabor patches, (2) disparity vergence responses (motor fusion) for large uniform disparities introduced by ophthalmic prisms, with either central or peripheral fusion stimuli, (3) disparity vergence responses to small binocular disparities that generally are within the normal range of haplopic stereoscopic depth perception for observers with normal binocular vision, and (4) depth discrimination functions for the absolute disparities used to study disparity vergence responses with haploptic stimuli.

**Stereoacuity**

The stimuli for measurements of stereoacuity were vertically separated Gabor patches, an upper reference stimulus, and a lower test stimulus producing a horizontal bandwidth of approximately 0.5 octaves. The test and reference stimuli, with 50% contrast, were presented for 500 ms, and the subject used a handheld response switch to report the direction (nearer or farther) of perceived depth of the test stimulus with respect to the zero-disparity reference target. Feedback was provided when the response was correlated appropriately with the sign of binocular disparity.

Psychometric functions were based on 400 trials (method-of-constant stimuli for five crossed and five uncrossed disparities), using ranges of disparity that were determined by preliminary measurements, to produce reliable depth discrimination for the largest disparities. As illustrated in Figure 1, for data analysis, the percentages of nearer responses were plotted as a function of stimulus magnitude, where stimuli with uncrossed disparities arbitrarily were designated as negative values. Using this convention, the normal psychometric function varied from zero near responses for the largest uncrossed disparities to 100% near responses for the largest crossed disparities. The psychometric functions were fitted with a logistic function\(^{20,21}\) to determine the psychophysical threshold, taken as the binocular disparity necessary to raise the depth discrimination rate from chance (point of subjective equality [PSE]) to 75% correct discrimination (i.e., the semi-intraquartile range; [SIQR]). Each subject’s stereoacuity was based on the mean from two sessions.

In some subjects, stereoacuities also were assessed with dynamic random-dot stereograms.\(^{19}\) The random-dot stereograms were squares
of 13 arcdeg per side in overall size with a central square of 4.3 arcdeg presented with stereoscopic depth. The individual dot elements, 6.7 ∗ 6.7 arcmin in size, were correlated between the two half-views of the stereogram, but each dot changed from dark to light with a probability of 0.5 between successive views at 60 Hz. The general procedures for data collection and analysis were the same as described earlier for the Gabor stimuli.

Prism-Induced, Disparity Vergence Responses
Disparity vergence responses were assessed by conventional psychophysical methods for measurements of fixation disparities, using a dichoptic nonius alignment procedure. For investigations of vergence responses to peripheral fusion stimuli, the nonius stimuli were superimposed on a high-contrast (83%) cosine grating with the central 2 arcdeg blanked by a single cycle of a 0.5-cyc/deg. raised cosine grating. The extended grating pattern was 12 arcdeg in width by 6 arcdeg in height. The nonius stimuli were drawn into the central region as dark bars that were 5.5 arcmin wide by 55 arcmin high. To eliminate monocular localization cues, the position of the upper nonius line (reference stimulus) was varied randomly within the central 1° of the stimulus field, and the relative contrast of each line was varied randomly between 0% and ±30% from trial to trial. The lower nonius line (test stimulus) could be offset to the right or left side of the reference stimulus in multiples of one pixel increments (±3.3 arcmin).

The subject reported the apparent relative direction of the lower test stimulus, with respect to the upper reference, with a handheld response switch. Monoptic and dichoptic nonius stimuli were interwoven, and auditory feedback was provided when the direction of the nonius offset and the subject’s response were in agreement.

For the studies of disparity vergence responses to central stimuli, the binocular fusion stimuli were 2.5-cyc/deg Gabor patches. The SD dichoptic nonius alignment procedure. For investigations of vergence responses to peripheral fusion stimuli, the nonius stimuli were superimposed on a high-contrast (83%) cosine grating with the central 2 arcdeg blanked by a single cycle of a 0.5-cyc/deg. raised cosine grating. The extended grating pattern was 12 arcdeg in width by 6 arcdeg in height. The nonius stimuli were drawn into the central region as dark bars that were 5.5 arcmin wide by 55 arcmin high. To eliminate monocular localization cues, the position of the upper nonius line (reference stimulus) was varied randomly within the central 1° of the stimulus field, and the relative contrast of each line was varied randomly between 0% and ±30% from trial to trial. The lower nonius line (test stimulus) could be offset to the right or left side of the reference stimulus in multiples of one pixel increments (±3.3 arcmin).

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For the studies of disparity vergence responses to central stimuli, the binocular fusion stimuli were 2.5-cyc/deg Gabor patches. The SD of the vertical filter was 2 arcdeg, and the SD for the horizontal filter was 0.4°. The nonius stimuli were presented in the central field of view by blanking the monitor screen for two frames before presentation of the nonius alignment stimuli. All other aspects of the studies of motor fusion with central fusion stimuli were identical with the studies with peripheral fusion stimuli.

Across sessions, vergence responses were assessed for a series of ophthalmic prism powers that approached the convergence and divergence limits of the subject’s fusion range. For each prism power, a psychometric function for discrimination of visual direction was based on 400 trials (method-of-constant stimuli for five rightward and five leftward offsets), using a range that had been determined by preliminary measurements for each subject. The analysis of the psychometric data for visual direction with dichoptic nonius stimuli was similar to the analysis of depth discrimination. In the case of direction discrimination, the percentages of responses that the test stimulus appeared to be to the right side of the reference stimulus were plotted as a function of stimulus magnitude, where stimuli with leftward offsets were designated as negative values. Using this convention, the normal psychometric function varied from zero ‘right’ responses associated with the largest leftward offsets to 100% right responses for the largest rightward offsets. The psychometric functions were fitted with a logistic function to determine the alignment threshold, taken as the PSE for the subject’s fusion range.

Results
Stereoacuity
The disparity threshold for depth discrimination is a standard measure of the quality of binocular vision and one of the defining properties of microstrabismus. The present study used more rigorous methods for determining stereothresholds than do the standard clinical tests, and each subject was allowed extensive practice on depth discrimination, involving some training sessions with combined perspective and disparity cues, before the final measurements of stereoacuity. Examples of the psychometric functions for stereoscopic depth discrimination are presented in Figure 1 for nonstrabismic subjects and in Figure 2 for strabismic subjects.

The functions for AEK and ENU (Figs. 1A, 1B) are typical of those for subjects with normal binocular vision, with stereoacuities that were generally less than 30 arcsec, whereas AMS and EDR (Figs. 1C, 1D) were clearly stereodeficient, with stereoacuities that exceeded 1000 arcsec. Even though the range of disparities was large, the stereo-deficient observers responses for perceived depth were dependent on the sign and magnitude of binocular disparity, with full stereovision of the stimuli based on stereoscopic depth. Similarly, all the strabismic subjects demonstrated some degree of stereoscopic depth discrimination, although their stereothresholds were substantially abnormal. For example, the functions for the subjects with infantile strabismus (Figs. 2A, 2B) demonstrated a trend that is indicative of stereoscopic depth, but the psychometric functions were very noisy, especially for uncrossed disparities. In...
Stereoacuity: non-strabismic subjects

Each case for microstrabismic subjects, their responses varied more systematically with the sign and magnitude of binocular disparity, but the disparity range required to obtain reliable discrimination was much larger in the subjects with microstrabismus than in the subjects with normal binocular vision. The stereothresholds, based on the SIQRs of the psychometric functions, were from 20-times (subject KBH) to 100-times (subject RJC) higher for the subjects with microstrabismus than for the typical normal patient (e.g., subject AEK). Thus, each of the subjects with small angles of strabismus was able to discriminate between classes of stereoscopic depth. Conversely, substantially abnormal stereoscopic vision does not identify uniquely the condition of microstrabismus, because two other subjects in the study had equivalent stereodeficiencies even though they did not have any other signs of abnormal binocular vision.

One of the remarkable characteristics of the experimental subjects’ stereothresholds is that they were nearly identical both with and without compensation for the angle of strabismus. Without correction for the angle of strabismus, an esotropic ocular deviation creates a standing or pedestal disparity for the stereoscopic stimulus that could contribute to an elevated stereothreshold. Such an effect would be similar to the elevated stereothresholds of subjects with normal binocular vision when the disparity increments are superimposed on large pedestal disparities. As shown in Figure 3, each subject’s stereothreshold was essentially constant with or without prismatic compensation for the angle of strabismus to reduce the fixation (pedestal) disparity. Thus, the pedestal disparities may have limited the early development of stereopsis, but the abnormal stereothresholds associated with microstrabismus are not explained by standing pedestal disparities, although it must be noted that vergence eye movements during the measurements cannot be ruled out. However, it is important that the effect of prism compensation was similar for both small, local, contour-defined stereograms and large, random-dot stereograms, and the levels of stereodeficiency were not related to the angle of strabismus, within the limited range of deviations of these patients.

Prism-Induced, Disparity Vergence Responses

One of the defining characteristics of primary microstrabismus is the clinical presentation of central anomalous retinal correspondence with normal peripheral retinal correspondence. Typically, patients demonstrate anomalous retinal correspondence on the Bagolini test or the Worth dot test, but have normal correspondence and normal fusion ranges for prism-induced fusional vergence. These differences suggest that the state of correspondence and vergence response func-
tions may be different with central and peripheral fusion stimuli. For these studies, vergence responses to prismatic disparities were assessed by conventional psychophysical measurements, which involve the determination of the relative locations of dichoptic stimuli that produce identical visual directions for each eye. For subjects with normal retinal correspondence, strabismic or nonstrabismic, the procedure is a straightforward and highly accurate measurement of vergence response to the prismatic stimulus. For strabismic subjects with anomalous retinal correspondence, the procedure measures the subjective angle of strabismus, which differs from the angle of deviation of the visual axes but, nevertheless, should provide important information about the sensory mechanisms in microstrabismic patients.

Ophthalmic prisms introduce uniform binocular disparities by displacement of the images onto noncorresponding retinal...
locations and thereby elicit closed-loop motor fusion responses to reestablish single binocular vision. Measures of alignment offsets over a range of prism values were obtained from each subject to provide descriptive stimulus–response functions of their fusion mechanisms. An example of the fusion response to a 6-pd base-in vergence stimulus for a subject with normal binocular vision is illustrated by the data in Figure 4. The psychometric function, representing the perceived visual directions of the dichoptic nonius stimuli, shows that the perception of common binocular visual directions (PSE) required a dichoptic alignment offset of 9 arcmin that was classified as a crossed or esotropia disparity. The relationship between alignment thresholds (eso- or exodeviations based on the mean from two sessions) and the power of vergence stimulus (base-in or base-out prism power) described each subject’s subjective alignment function.

Examples of the alignment offset as a function of vergence stimulus are presented for nonstrabismic (Fig. 5) and strabismic (Fig. 6) observers for two types of fusion stimuli, a central fusion stimulus (open symbols) and an extended peripheral fusion stimulus (closed symbols). Although the forms of the disparity stimulus–response functions were variable across subjects, the important observation is that, in nonstrabismic subjects, the functions for each subject were indistinguishable with central versus peripheral fusion stimuli, whereas in the strabismic observers the functions were clearly different.

The data for the nonstrabismic observers are typical of the fixation disparity–forced-vergence data that have been described for normal single binocular vision. In these cases, the binocular disparities introduced by the ophthalmic prisms elicited reflexive fusion movements that reestablished single binocular vision. However, because of Panum’s fusional areas, exact binocular fixation is not necessary for single binocular vision and, thus, the subject’s vergence response was often incomplete. The residual binocular disparity associated with a vergence error is the fixation disparity, and its magnitude (the difference between the vergence stimulus and vergence response) is a measure of the accuracy of the vergence response.22

In each of the examples for nonstrabismic subjects (Fig. 5), the vergence error was small with low prism powers and increased with the magnitude of the fusion stimulus. The fusion stimulus that results in a zero alignment offset (the associated phoria) is a measure of the location of the horopter, or where the subjective and objective properties of the stimulus coincide. These common characteristics of the fixation disparity–forced-vergence functions were the same in subjects AMS and EDR (Figs. 5C, 5D), who had deficient stereoscopic depth perception, as they were in the two subjects PMF and ENU (Figs. 5A, 5B) with normal stereoscopic vision. Thus, these data are further evidence for the independence of motor and sensory fusion responses beyond the initial disparity-selective mechanisms in primary visual cortex.

In contrast to the fusion response functions in nonstrabismic observers, the nonius alignment functions of the strabismic observers with central fusion stimuli were markedly different from the responses with peripheral fusion stimuli. First, to illustrate response functions with extremely compromised binocularity, the data for subject ADH (Fig. 6A; filled symbols) demonstrate characteristics that are not consistent with normal sensory or motor fusion. Although ADH had sensory alignment with prismatic compensation for the angle of strabismus (10° base-in), the flat response functions for both divergence and convergence stimuli were descriptive of alignment responses associated with anomalous correspondence, suppression, or voluntary convergence.22 Apparently, in this patient, the combination of infantile exotropia with consecutive exotropia after two surgical eye alignments has caused extreme motor and sensory adaptations that are not compatible with binocularity.

The alignment functions with peripheral fusion stimuli (filled symbols; Fig. 6) of all the other strabismic subjects generally reflected more normal binocularity, with normal retinal correspondence and a small range of motor fusion centered on the angle of strabismus. In all these cases, the zero alignment offset occurred with prismatic powers that were approximately equal to the magnitude of strabismic deviation, designated by the arrows pointing to the abscissa in each graph. Although the point of concurrence for subjective and objective alignment was consistent with normal retinal correspondence, the alignment functions were very steep, with a relatively narrow response range in comparison to nonstrabis-
mic subjects (Fig. 5) and thus imply that the disparity vergence mechanisms of these subjects do not possess the normal, rapid-adaptation responses that typify normal binocular vision. Nevertheless, although eye movements were not monitored objectively, peripheral fusion stimuli appeared to elicit vergence disparity responses over a small response range that usually does not include an orthotropic eye alignment. The functions for the subjects with microstrabismus, therefore, are in agreement with the typical clinical finding of peripheral fusion with near-normal amplitudes.

Another typical clinical finding in microstrabismus, harmonious anomalous retinal correspondence with foveal stimulation, was demonstrated by the alignment functions with central fusion stimuli (open symbols; Fig. 6). The primary differences in normal and strabismic patients are apparent from comparisons of their functions with peripheral and central fusion stimuli. Whereas the functions of nonstrabismic subjects were identical for the two stimulus conditions (Fig. 5), the functions in strabismic subjects differed in ways that are predictable by a switch from normal to abnormal retinal correspondence with the change from peripheral to central fusion stimuli (Fig. 6). In every case, with foveal stimulation the subjective and objective alignments were concordant with habitual strabismic viewing—that is, harmonious anomalous correspondence. The two subjects with infantile esotropia (ADH, JPT) showed harmonious correspondence over a range of prism stimuli, whereas the functions for the subjects with microstrabismus were generally parallel to the peripheral fusion functions with normal correspondence.

The results of the stereoacuity and disparity vergence measurements have provided detailed descriptions of three of the important clinical characteristics of primary microstrabismus: reduced stereocuity, normal peripheral fusion, and abnormal sensory fusion with foveal stimuli. These systematic disparity-dependent relationships indicate that patients with microstrabismus have disparity-sensitive mechanisms, at least for relatively coarse disparities, but the response characteristics do not corroborate a sensorial origin for microstrabismus. The characteristics of the disparity-dependent functions, especially identical stereoacuities, with and without compensation for the interocular misalignment, and different modes of retinal correspondence for central and peripheral stimuli, do not support the concept that microstrabismus is an adaptation to an inherent anomalous retinal correspondence. However, these data do not dispel the possibility that anomalies within a specific class of disparity-selective neural mechanisms could be the basic sensory abnormality underlying oculomotor misalignment in primary microstrabismus. Investigations of responses that are based on both the sign and magnitude of binocular disparity are needed to determine whether there are innate deficits in specific classes of disparity-selective mechanisms in microstrabismic patients.

Disparity Vergence Responses to Haplopic Disparities

To investigate further the types of anomalies of disparity-selective mechanisms that might underlie microstrabismus, we assessed oculomotor responses to binocular disparities within...
Subjective Angle of Strabismus: peripheral vs. central fusion stimuli

FIGURE 6. Fixation disparity as a function of prism-induced disparity vergence for subjects with strabismus. (A, B) Data for subjects ADH and JPT, the subjects with infantile esotropia. (C–F) Data for the subjects with primary microstrabismus. The magnitude of the subject’s strabismic deviations are indicated by the arrow (other details are presented in Table 1). For these plots, esotropia disparities (overconvergence) are represented as positive values and exotropia disparities (underconvergence) are represented as negative values on the ordinate. Base-in prism (divergence) stimuli are designated as negative values and base-out (convergence) stimuli are designated as positive values on the abscissa. For each subject, data are presented for two types of fusion stimuli, a central fusion stimulus (open symbols), and an extended peripheral fusion stimulus (closed symbols). Error bars, ± 1 SD.

the range of normal haplopia. Specifically, the initiation of open-loop vergence responses were determined independently for crossed and uncrossed disparities using small Gabor stimuli positioned centrally in the visual field. The quantification of vergence eye movements was based on psychophysical methods to obtain the PSE for dichoptic nonius alignment. Examples of the psychometric functions for perception of visual directions for two subjects, a control subject (ENU) and a microstrabismic subject (KBH), are illustrated in Figure 7. The data for ENU (Fig. 7A) exhibited an asymmetry in vergence responses for crossed and uncrossed disparities that is common in subjects with normal binocular vision. In this case, a stimulus disparity of 30 arcmin uncrossed disparity produced a divergence response of 14 arcmin, but a crossed disparity of the same magnitude failed to elicit a response. In comparison, the vergence responses produced by the same stimulus magnitudes were much smaller for the microstrabismic subject and, although there is a small asymmetry between convergence and divergence in the psychometric functions, the full functions (shown in Fig. 9) indicate a constant bias rather than an asymmetry in the disparity response function.

Across subjects with normal binocular vision, the direction and extent of asymmetrical responses were variable, as illustrated by the data from two of the control subjects in Figure 8A. In one example, the function for subject ENU demonstrates a proportional stimulus response for uncrossed disparities, but not a systematic relationship for crossed disparities. The complementary form of response pattern is illustrated by the data for subject CSK, which shows a proportional response for crossed disparities, but not for uncrossed disparities. These forms of response asymmetry between crossed and uncrossed disparities that were common in subjects with normal stereop-
sis were not evident in subjects with deficient stereopsis, even those with orthotropic eye alignment. The functions in the two stereo-deficient orthotropic subjects (Fig. 8B) show symmetrical and systematic responses to binocular disparities of either sign, implying that their oculomotor systems responded differentially to stimuli that were perceptually indistinguishable (see Fig. 10A).

The data from subjects with stereodeficiencies caused by strabismus were similarly symmetrical. However, it should be noted that in strabismic subjects, the disparity and alignment values refer to the physical relationships of the stimuli, and not necessarily the locations of corresponding points or the relative positions of the visual axes. For example, subject KBH (Fig. 9B) demonstrated harmonious anomalous correspondence with the small central-fusion stimulus used for these measurements and, therefore, without compensation for the angle of strabismus (circle symbols), a zero-stimulus disparity represents a zero functional disparity with respect to his retinal correspondence, but the same stimulus represents a large uncrossed functional disparity with respect to the esotropic eye.
alignment. It is, therefore, an important characteristic of microstrabismus that the responses to divergent and convergent stimuli are appropriate with respect to the anomalous correspondence rather than to the angle of strabismus. Additional prisms that partially (square symbols) or fully (triangle symbols) compensated for the angle of strabismus resulted in a small alteration in the overall location of the function, but not in the relative direction or magnitude of the subject's responses. Thus, the results for KBH and all the other microstrabismic subjects (Figs. 9C, 9D) demonstrated responses that were symmetrical for crossed and uncrossed disparities relative to their anomalous correspondence rather than relative to their eye alignment. Remarkably, the same systematic relationship between disparity and alignment threshold was found for subject JPT (Fig. 9A), whose angle of strabismus was larger than that in those with microstrabismus. The response magnitudes across disparities (i.e., the slopes of the vergence response functions) were within the range of normal subjects in all the strabismic patients, and therefore the data demonstrate that the disparity-induced responses have adapted to the angle of strabismus, but the functions do not provide evidence for an absence of a class of disparity-selective mechanisms.

Depth Discrimination of Absolute Disparities

The final investigations were designed to study abnormalities in the populations of disparity-selective mechanisms that are required for the normal perception of stereoscopic depth. Normal stereopsis requires neural mechanisms that are independently selective for crossed versus uncrossed disparities and for zero versus nonzero disparities. Therefore, to determine whether there are selective abnormalities for a class of disparity stimuli, a three-alternative, forced-choice procedure was used. The three-alternative procedure was necessary because two-alternative discrimination (i.e., the discrimination between near versus far depth) can be accomplished by an exclusion of one response type from an absence of depth perception for a class of disparity-selective mechanisms. Presumably, however, the stimuli for the anomalous class of mechanisms could not be differentiated from the stimuli with zero disparity, especially for stimuli presented for a brief duration without a simultaneous depth reference.

Results of the investigations of depth discrimination are presented in Figure 10 as the detectability index (d-prime) as a function of the sign and magnitude of disparity. The differences in the forms of the functions that are expected for normal and deficient stereopsis are presented in Figure 10A by the data for a control subject (ENU) and for one of the stereodeficient, orthotropic subjects (EDR). The difference in their stereopsis is obvious: ENU’s very steep detectability function demonstrates that she had nearly perfect discrimination between the three types of stimuli and for the direction of depth for even the smallest disparities presented. In comparison, the
function for EDR was essentially flat and reflected chance
certainty for disparities of any magnitude—that is, under
these stimulus conditions he was not able to discriminate
between near versus far versus zero stereoscopic depth.

The results for the microstrabismic subjects fall between
the two extremes of normal stereopsis and stereoblindness.
The data for three of the subjects (Fig. 10B–D) show discrim-
ination functions that correlate weakly with binocular dis-
parity, in agreement with their defective stereopsis that was
demonstrated by the measurements of stereoacuity. However,
in contrast to the stereoacuity data, compensation for the stra-
бismic deviation improved depth perception for KBH, although
not for subject HRC. More important, the disparity response
functions did not show differences in detectability between
crossed and uncrossed disparities that indicate an innate ab-
sence of a specific class of disparities of the central retina, but not the periph-
eral retina. In addition, the data do not provide evidence of a

**DISCUSSION**

The results of these investigations have demonstrated that
patients with primary microstrabismus have a relatively high
grade of binocular vision, but they do not directly support a
specific sensory abnormality as the cause of the small ocular
development. For example, the data do not support the hypothesis
that microstrabismus is an oculomotor adaptation to an inher-
tent anomalous correspondence because the state of correspon-
dence is dependent on the retinal locations of the fusion
stimuli, which would require specific genetic alterations for
disparity mechanisms of the central retina, but not the periph-
eral retina. In addition, the data do not provide evidence of a

**FIGURE 10.** Depth-discrimination functions. (A) Data for a subject with
normal binocular vision (ENU) and an orthotropic, stereodeficient sub-
ject (EDR). (B–D) Data from microstrabismic subjects. In two of the mi-
crostrabismic subjects KBH (B) and HRC (C), depth discrimination func-
tions are presented with prismatic compensation (circles), or without
compensation (squares) for the strabismic deviation. The data represent
the detectability index (d-prime) as a function of the sign and magnitude
of disparity in a three-alternative, forced-choice depth discrimination
task. For purposes of data presenta-
tion, negative values were assigned
to uncrossed disparities and positive
values to crossed disparities, but d-
prime values of higher absolute value
indicate more highly detectable stim-
uli, regardless of the sign of the value.
large number of observations to develop the psychometric function. In spite of these differences, the assessments of stereopsis were generally similar to those of other studies using clinical tests.3–6,52,53 For example, Helveston and von Noorden found some degree of stereopsis with the Wirt test in all their microstrabismic patients with eccentric fixation, Cleary et al.,5 found very high levels of stereoaucity with the Frisby stereotest in five of nine patients with primary microstrabismus, and recently, Tomac et al.6 reported that one half of their patients with primary microesotropia achieved at least gross stereopsis on the Titmus stereo-fly test.

The present studies have extended these findings to demonstrate two important properties of microstrabismus. First, stereoaucities with microstrabismus are basically the same whether they are obtained with or without compensation for the strabismic deviation (Fig. 3). This result may simply reflect the effect of abnormal binocular vision during early development. When an interocular deviation in young children causes large, off-horopter disparities in fixated objects, the fine-disparity mechanisms are deprived of adequate stimuli for normal development, whereas allowing normal development of coarse-disparity mechanisms for both central and peripheral stimuli. Consequently, in later life, the level of stereoaucity would be limited by coarse-disparity mechanisms for either bifoveal stimuli or foveal–peripheral stimuli with a strabismic deviation.

A second important finding of the present investigation relates to local versus global stereopsis in microstrabismus. It has often been reported that patients with microstrabismus rarely perceive depth in random-dot stereograms,7,55 yet for the two subjects that were tested, stereoaucities were equal for local and global stereopsis (Fig. 3). These measurements of stereoaucity probably were accomplished because of the specific configuration of the random-dot stereograms, because the mechanisms of disparity-detection should not be different for different forms of stereograms. The clinical versions of random-dot stereograms are small, with small dot elements that must be in precise registration on the two retinas for normal stereoprocessing. These stereograms easily could become decorrelated for strabismic patients by their interocular deviation. The present study used stereograms with extended overall size and large dot elements, so that peripheral fusion could maintain interocular correlation and the strabismic deviation would not decorrelate the two stereoscopic half-views.

The study of motor fusion also provided evidence of high grades of binocularity with responses that were based on either normal or anomalous retinal correspondence, depending on the retinal locations of the stimuli. Similar results with other types of strabismic patients have been reported previously.54–56 The general finding of oculomotor fusion responses in strabismic patients also is in agreement with previous investigations, including the demonstration that the vergence responses can be centered on disparities referenced to the subjective angle (anomalous retinal correspondence) rather than the objective angle of deviation.57–59 However, vergence responses do not represent a simple shift in zero retinomotor sites, because clinical data have shown that microstrabismic patients have normal peripheral correspondence andfusion amplitudes for prism-induced disparities, even though they have anomalous correspondence by central vision tests.3–59 Thus, the coexistence of harmonious anomalous retinal correspondence for small central stimuli and normal fusional response magnitudes for the peripheral, uniform disparities introduced by ophthalmic prisms is a defining characteristic of microstrabismus. The present investigations of prism-induced disparity vergence also found fusion responses that were mediated either by normal correspondence when the fusion stimuli were located peripherally or mediated by anomalous correspondence when the fusion stimuli were restricted to the central visual field (Fig. 6). The two states of retinal correspondence produce an interesting dilemma for the strabismic visual system because, under normal binocular viewing, central and peripheral stimuli present conflicting vergence stimuli. Apparently, however, the strabismic adaptation is to ignore the larger disparities associated with nonfixated objects and to respond only to fixated stimuli, using anomalous correspondence. Such an adaptation actually represents an exaggerated response of normal mechanisms of binocular vision, because normal subjects also are relatively insensitive to large disparities from stimuli that are off the horopter, which even for the normal visual system is advantageous for maintaining stable normal eye alignment.53–55 Therefore, just as in large-angle strabismus, anomalous correspondence in microstrabismus may be an adaptation to an oculomotor anomaly that occurs only in central vision, because there are other mechanisms that render the visual system insensitive to large disparities associated with nonfixated objects.

The properties of the abnormal binocularity with microstrabismus seem to be described adequately by developmental constraints and adaptations imposed by visual experience during early childhood, rather than genetic or acquired errors in visual development, whereas allowing normal development of coarse-disparity mechanisms for both central and peripheral stimuli. Previous investigations of the vergence responses were centered on the point of subjective alignment.43 However, vergence responses were centered on disparities referenced to the subjective angle (anomalous retinal correspondence) rather than the objective angle of deviation.57–59 In the present investigations, the vergence loop was opened by using stimulus durations that were shorter than the combined latency-plus-eye movement time. Another important methodological consideration was the use of fusion stimuli (small central Gabor patterns) that elicited anomalous retinal correspondence for the subjects with primary microstrabismus, and therefore the positive and negative vergence responses were centered on the point of subjective alignment with anomalous retinal correspondence. In other respects and with some caution because of the possible effects of anomalous retinal correspondence, the results for microstrabismic patients appear to be normal response functions for disparity vergence to stimuli of relatively small magnitude (Fig. 9). In fact, the data for those with microstrabismus are indistinguishable from the data of subjects with stereodeficiencies of no known etiology (Fig. 8B). Notably, the data for both types of sensory deficits in disparity processing demonstrate vergence responses that were proportional to stimulus magnitudes and continuous across crossed and uncrossed physical disparities.

The systematic relationship found under these experimental conditions reveals two interesting characteristics of the
anomalous retinal correspondence in microstrabismus. First, the time constraints for these experiments, a brief (250 msec) fusion stimulus and a two-frame interval (16.66 msec) between the Gabor fusion stimuli and nonius response stimuli, effectively precludes mechanisms based on a disparity-induced remapping of retinal correspondence.\textsuperscript{5,52} Second, the disparity vergence functions suggests that the subjects’ disparity vergence mechanisms were as sensitive to small disparities, with the same response amplitude, as subjects with normal retinal correspondence. Further, the normal response function, given the imposed timing paradigm, indicates that the vergence response latencies were also within normal limits. Thus, all the primary response characteristics of their disparity vergence seem to be normal, except that the zero retinomotor location is displaced to a nasal retinal site in the deviating eye.

Another etiological factor that has been proposed for microstrabismus is a genetic–hereditary deficiency in one of the components of disparity-selectivity. The data from the present experiments argue against such an etiological factor by the linearity in vergence responses to crossed and uncrossed disparities (Fig. 9) and in the detectability of crossed and uncrossed disparities (Fig. 10). Mild asymmetries in the sensitivities of disparity-sensitive mechanisms of the type that could cause strabismus are quite common in subjects with normal binocular vision and may account for the occurrence of fixation disparities.\textsuperscript{13,14,53,54} However, if the constant frank deviation of microstrabismus is an expression of abnormal imbalances of disparity-selective mechanisms, then the response functions for depth detection and/or disparity vergence should have revealed strong response biases. Such response biases were not present in the disparity functions of subjects with primary microstrabismus, although the sensory disparity detection functions were very shallow. Therefore, these functions demonstrate an independence in sensory and motor sensitivities that is similar, but more apparent, than equivalent data from subjects with normal binocular vision. In this respect, the poor correlation between sensory and motor mechanisms of disparity processing may be considered to be another example of the exaggerations of normal mechanisms of binocular vision that are caused by abnormal visual experience.

Two additional aspects of these experiments are important to the general implications of the results. First, the experimental subjects were a much more homogeneous subgroup of primary microstrabismus than in previous investigations.\textsuperscript{2–6} None of the subjects of these experiments exhibited the commonly associated conditions of anisometropia, amblyopia, or eccentric fixation. Second, all the subjects, both the experimental and control groups, were given extensive pretraining on the procedures and observations required for data collection. Consequently, the data should provide a fair representation of the state of their binocular vision, without influence from cognitive factors or naivety in making abstract judgments. Thus, it may be concluded that this specific form of primary microstrabismus represents a highly adapted state of binocular vision.\textsuperscript{55} with stable eye alignment, coarse depth perception, and central harmonious anomalous retinal correspondence. It is an interesting condition, and much more work is needed to gain a full understanding of the mechanisms of binocular vision, but patients with this form of primary microstrabismus are not apt to benefit from additional treatment by either medical or nonmedical procedures.

Acknowledgments

The authors thank Bruce Wick, Janice Wensveen, and Suzy Wickham for the orthoptic workup and referral of their patients with primary microstrabismus.

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