
Dynamic vergence eye movements in strabismus and amblyopia: symmetric vergence

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Dynamic vergence eye movements in response to step target displacements along the midline were measured by an infrared reflection technique in 11 patients having either intermittent strabismus, constant-strabismus amblyopia, or amblyopia without strabismus. We found the absence of normal disparity (fusional) vergence in all patients having strabismus and in some patients having amblyopia without strabismus. A characteristic response consisting of a binocular accommodative vergence component and an early binocular saccadic component was used to foveate the target of interest with the dominant eye. Vergence responses in our control subjects and patients with the nondominant eye occluded were similar to those recorded in our patients during binocular viewing. These results suggest that disparity information is not utilized by patients, probably as a result of long-term, ongoing suppression in the deviated or amblyopic eye. Accommodative vergence with the aid of an early foveating saccade was the primary mechanism for tracking targets in three-dimensional space.

Key words: strabismus, amblyopia, vergence, eye movements, Hering's law, accommodation

Vergence eye movements in patients with strabismus and amblyopia have been inferred from patients' subjective responses to disparate stimuli presented simultaneously to each eye, rather than objectively recorded and quantified (for a review of early work, see Burian and von Noorden¹). Burian,² following Bielschowsky³ and Schlodtmann,⁴ be-

lieved that some strabismic patients could produce "fusional movements" when disparate stimuli, placed in the peripheral retina of each eye, were reported fused. Patients reported changes in the localization of two haplopic fiducial marks located in the center of the visual field, and this was interpreted as evidence for actual eye rotations. Halldèn⁵ confirmed Burian's finding in patients having anomalous retinal correspondence (ARC). He similarly defined *fusional movements* as a return to the no-disparity condition in the central field following the introduction of a disparity. In Halldèn's study, changes in subjective localization of targets were estimated by haploscopic techniques, and from this he calculated changes in vergence angle. These fusional movements took several minutes to complete, and static measurements of target locations were made only about once a minute. However, in none of the above studies were eye movements objectively recorded.

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Mariani and Pasino⁶ criticized Burian's study and pointed out that other factors could account for his results. They referred to Kretschmer,⁷ who showed that changes in the angle of anomaly rather than true fusional movements could be the mechanism employed to fuse disparate targets. (The angle of anomaly is measured from the fovea in the nondominant eye to a point in the nondominant eye that corresponds to the same visual direction as the fovea of the dominant eye.) From their own experiments on fusion in strabismic patients, still without objective eye movement recordings, Mariani and Pasino⁶ inferred that most patients changed the angle of anomaly instead of performing true fusional movements, thus confirming Kretschmer's findings.

In an attempt to reconcile these differences and further extend these observations, we objectively recorded dynamic vergence eye movements in 11 patients having either constant-strabismus amblyopia, amblyopia without strabismus, or intermittent strabismus, while changing binocular fixation between near and far midline targets. These targets produced disparity by changing distance from the patients as is found in normal everyday binocular viewing. Quantification of the dynamic aspects of the vergence response in these patients shows the absence of normal disparity vergence movements and the use of normal accommodative vergence eye movements and saccades to track targets in three-dimensional space.

Methods

Binocular horizontal eye position was recorded by an infrared reflection method.^{8,9} The recording system had an overall bandwidth of 150 Hz, a linear range of at least $\pm 7^\circ$, and a noise level of 6 min arc. The infrared method does not distinguish between eye rotation and eye translation; hence, translational movements, if large enough, could introduce artifacts in the eye movement recordings. However, Krishnan and Stark,¹⁰ using a method that distinguishes between rotation and translation, have shown that eye translation during saccadic or vergence eye movements is minimal. Furthermore, using data from Fry and Hill,¹¹ they estimated that the translational movement of the

eye would only be 0.01 mm or 0.05° for a 10° rotation, below the noise level of our recording system.

To ensure that the responses were independent of the target system, two systems were used to stimulate vergence. In each system, targets were placed along the subject's midline at 25 and 50 cm away from the estimated center of rotation of each eye. These targets were carefully adjusted in both horizontal and vertical planes to minimize occurrence of eye movements resulting from target misalignment. In one system, the two targets consisted of small Lucite plates with fine crosses etched in the front surfaces subtending visual angles of 1.5° and 3.0° for the far and near targets, respectively. The fine lines of the crosses subtended angles of 2 and 4 min arc for the near and far targets, respectively. A miniature bulb (GE 222) was installed to provide target illumination of the etched cross alone. In the other system, targets were made from strips of exposed film with fine crosses etched into the emulsion, and the targets were mounted in front of a 2 cm square holder and back-illuminated by a grain-of-wheat filament bulb through a light diffuser. The holders for the far and near targets subtended angles of 2.3° and 4.5° , respectively. The fine lines composing the crosses subtended angles of 2 and 4 min arc for far and near targets, respectively.

The luminance of the targets was measured with an S.E.I. photometer under the same low photopic illumination conditions used during the experiments. The luminance for the Lucite plates measured 0.5 log ft-lamberts. The contrast for these targets with the formula $(I_{\max} - I_{\min}) / (I_{\max} + I_{\min})$ was 0.53. For the second system using the exposed film, the target luminance measured 1.7 log ft-lamberts and the contrast was 0.93.

Experimental procedures were adapted to the clinical situation and thus kept as simple and as uniform as possible. Targets were alternately illuminated in a pseudorandom sequence by the experimenter. Each subject was instructed to keep the illuminated target clear and single at all times. These procedures were performed (1) with both eyes viewing and (2) with the nondominant eye covered but still allowing eye movements to be recorded from both eyes. Calibrations were performed before, during, and after each brief experimental run.

Eleven patients having strabismus and/or functional amblyopia and two normal control subjects participated in the study. Patients were recruited from the general clinic at the School of Optometry, University of California, Berkeley. All

Table I. Clinical data of subjects

Subject	Age	Prescription	Visual acuity	Vergence abnormality	Eccentric fixation	Correspondence and stereoacuity*
Constant-strabismus amblyopia:						
B. S.	25	LE +2.00 = -0.25 × 130 RE +2.25	20/25 20/15	1-2 ^Δ ET LE	½ ^Δ nasal LE	ARC 200"
D. F.	23	LE +3.75 = -0.50 × 165 RE +0.50	20/30 20/15	18 ^Δ ET LE	1 ^Δ nasal LE	— 400"
J. K.	15	LE -1.50 RE -1.75	20/122 20/20	10 ^Δ ET LE; 1 ^Δ HT LE	2.5 ^Δ nasal; 2 ^Δ superior LE	ARC 300"
B. B.	33	LE +0.75 = -0.50 × 40 RE +0.25 = -0.50 × 180	20/630 20/10	5-6 ^Δ ET LE; 2 ^Δ HT LE	2.5-3.5 ^Δ nasal; 3-4 ^Δ superior LE	— —
Amblyopia without strabismus:						
S. H.	24	LE -0.75 = -2.00 × 90 RE pl = -0.50 × 19	20/38 20/20	None	2 ^Δ nasal; 2 ^Δ inferior LE	NRC 100"
L. T.	25	LE -2.50 = -1.25 × 172 RE -5.00 = -0.75 × 5	20/25 20/40	None	2 ^Δ Nasal; 2 ^Δ inferior RE	NRC 60"
B. W.	19	LE +5.00 RE +3.00	20/110 20/15	None	2 ^Δ temporal LE	NRC 400" → 60"
Intermittent strabismus without amblyopia:						
J. L.	13	LE +0.75 RE +0.50	20/20 20/20	20 ^Δ ET RE; 6 ^Δ HT RE	Jerk nyst.	UHARC† —
B. N.	31	LE -5.00 RE -4.50 = -0.75 × 20	20/20 20/20	15 ^Δ XT LE	Central, steady LE, RE	ARC 40"
Former strabismus patients:						
J. W.	24	LE -5.00 RE -2.50 = 0.75 × 165	20/15 20/25	6 ^Δ EPH	None	NRC 140"
J. B.	25	LE -0.75 = -0.50 × 8 RE -2.75 = -0.75 × 90	20/25 20/30	10 ^Δ EXPH 2 ^Δ HPH	None	NRC —
Control subjects:						
B. L.	29	LE Plano RE Plano	20/20 20/20	None	None	NRC 40"
A. D.	23	LE +8.0 = 0.25 × 175 RE +8.0	20/20 20/20	None	None	NRC 40"

ET = esotropia; XT = exotropia; ARC = anomalous retinal correspondence; NRC = normal retinal correspondence.

*At least as indicated.

†Unharmonious ARC.

patients had a thorough vision examination and were free from ocular or neurological disease. They were classified into three major groups: constant strabismus with varying degrees of amblyopia, amblyopia without strabismus, and intermittent strabismus without amblyopia. In some patients classified as amblyopic, the visual acuities were less than 20/40 in the nondominant eye. In these cases, the criterion of a two-line difference between the visual acuities of the two eyes was used to define amblyopia. This method is standard clinical practice.^{12, 13} The subjects' ages ranged from 10 to 33 years, with an average age of 25. A summary of each subject's clinical findings is presented in Table I.

It should be noted that what is called "disparity" vergence in this paper has been known as "fusional" vergence in the past. We prefer to use the term *disparity* rather than *fusional* because disparity drives the vergence system and fusion is usually a higher-level perceptual result following these movements.

Results

Absence of disparity vergence in patients. Typical disparity vergence eye movements produced by changing fixation between near and far midline targets were characterized by a 160 to 200 msec latency followed by

Previous surgery or therapy	Vergence abilities	
	40 cm Base in ^Δ Base out ^Δ (break/ refusion)	6 m Base in ^Δ Base out ^Δ (break/ refusion)
Age 16	—	—
Surgery	8/4	14/8
Age 6	18/10	—
Surgery	6/2	—
None	24/14	15/10
	24/15	6/3
Age 8	—	—
Surgery	—	—
None	24/16	36/26
	14/10	4/2
None	38/10	32/14
	27/22	4/2
Age 17	—	—
Orthoptics	—	—
Age 2	—	—
Surgery	—	—
Age 16	40/doubled	40/doubled
Surgery	24/doubled	8/doubled
Age 3	28/18	16/10
Surgery	32/18	32/30
Age 8	—	—
Surgery	—	—
None	—	—
	—	—
None	—	—
	—	—

smooth, equal, disjunctive movement of the eyes.¹⁴⁻¹⁸ The response in Fig. 1, *a*, of a control subject exemplifies a normal response. At times, the vergence contained a small saccade as seen during the divergence response of Fig. 1, *a*.

In contrast, most patients with strabismus and/or amblyopia did not perform normal disparity vergence responses. Although the latencies were normal, these patients made unequal vergence movements in each eye as shown in Fig. 1, *b*. The vergence amplitudes were always smaller in the dominant eye than in the fellow eye; the average vergence

amplitude of the dominant eye was approximately 18% of that of the fellow eye. In these responses, the unequal vergences were accompanied by a binocular saccade that served to place the fovea of the dominant eye close to the new target. The combination of this saccade and the small amplitude vergence functioned to place and maintain the dominant eye on the new target.

This pattern of unequal vergence amplitudes accompanied by a saccade characterized all the responses made by patients having intermittent strabismus without amblyopia. Eye movement responses in Fig. 1, *b*, display the typical response found in Patient B. N. (see Table I) and the other patient in this diagnostic group. In each response, the vergence in the dominant eye was much less than that found in the fellow eye. For example, the convergence amplitudes in Fig. 1, *b* equaled 0.8° and 9.0° for the dominant and nondominant eyes, respectively. For both convergence and divergence responses, the percent vergence amplitude in the dominant eye equaled 11% of that found in the nondominant eye.

Patients with constant-strabismus amblyopia responded similarly. A representative example is seen in the eye movement responses of Subject J. K. (Fig. 2, *a*). Responses showed an absence of normal disparity vergence similar to those found in the previous patient (Fig. 1, *b*), having intermittent strabismus. Here, too, the unequal vergence amplitudes that occurred during both convergence and divergence, had lower amplitudes in the dominant left eye than in the fellow eye. For example, the convergence amplitudes equaled 0.8° and 4.5° for the dominant and nondominant eyes, respectively. For these records, dominant eye vergence amplitudes measured 18% of those in the fellow eye for both the convergence and divergence.

In contrast to patients with strabismus, not all amblyopic patients exhibited these abnormal vergence responses. Of three patients having amblyopia without strabismus, only L. T. performed normal vergence responses at all times; another amblyope,

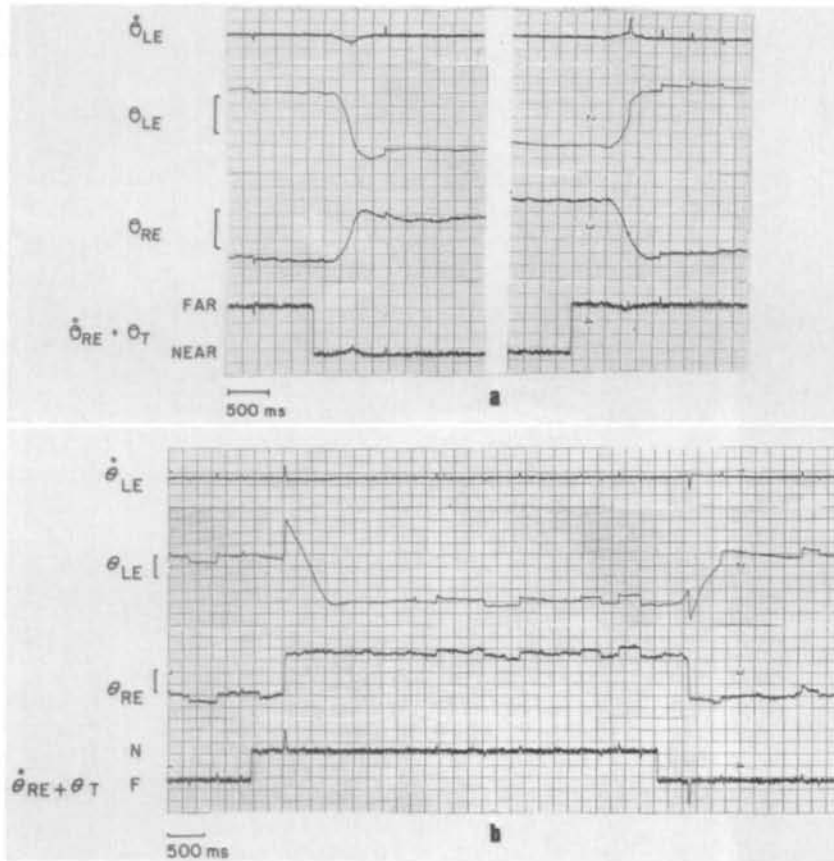


Fig. 1. Symmetric vergence condition. Symbols for all figures unless otherwise noted: θ_{LE} = left eye position; θ_{RE} = right eye position; $\dot{\theta}_{LE}$ = left eye velocity; $\dot{\theta}_{RE} + \theta_T$ = right eye velocity summed with target position. Downward deflections represent rightward movements; calibration bars for position represent 2° , and time markers represent 500 msec. a, Control Subject B. L. shows normal response to symmetric vergence stimuli. b, Patient B. N. having intermittent strabismus without amblyopia exhibits abnormal response, contrary to normal control subject responses in a. Following target changes, vergence occurs primarily in left eye only. Saccade occurring early in response is used to foveate new target with right eye; note unequal saccades occurring during vergence response, but equal saccades during extended fixation periods.

B. W., always produced abnormal vergence responses similar to those of the strabismic patients; the last amblyope, S. H., had brief intermittent episodes of normal vergence but only during convergence. Eye movements from Patient S. H. are shown in Fig. 2, b; the vergence amplitudes in the dominant eye equaled 6% of those in the amblyopic eye.

Monocular viewing of midline targets. When one eye was occluded, the responses of the control subjects to the symmetric ver-

gence stimuli resembled those responses produced by all strabismic patients and some nonstrabismic amblyopic patients under binocular viewing conditions. The response of Control Subject B. L. with the right eye covered is shown in Fig. 3. The vergence responses seen in this figure contained only an accommodative vergence component due to the occlusion of one eye. This is to be expected since disparity vergence requires a binocular stimulus; occluding one eye dis-

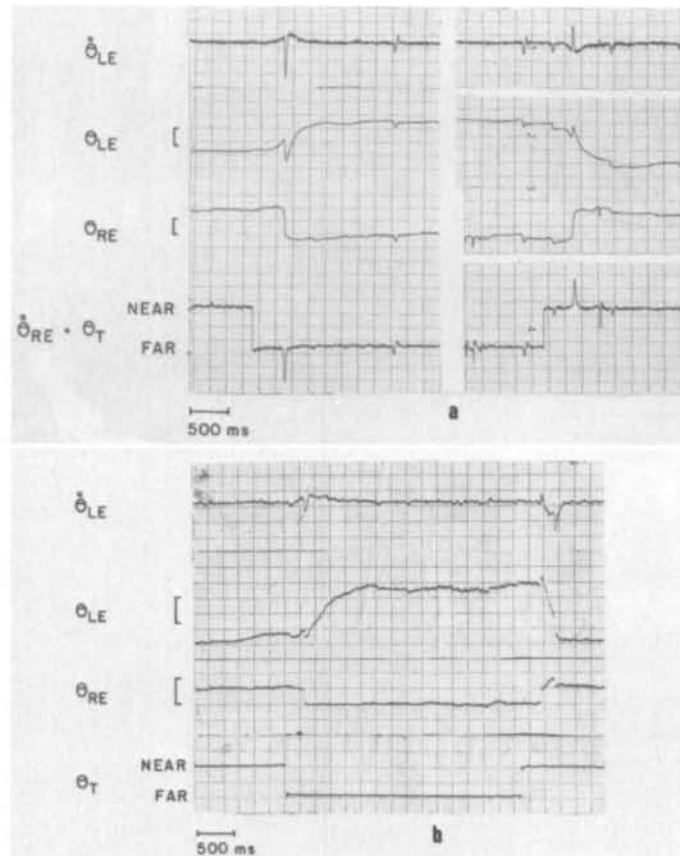


Fig. 2. Symmetric vergence condition. a, Patient J. K. with constant strabismus amblyopia, showing similar abnormal responses consisting of predominant vergence in amblyopic left eye, early foveating saccade in dominant right eye, and non-Hering's law saccades during response, especially for convergence. b, Patient S. H. having amblyopia without strabismus. Similar abnormal responses also found in this patient, but they only occurred intermittently.

ables the disparity vergence control system. Characteristically, the amplitude is smaller in the viewing eye than in the covered eye during accommodative vergence.^{9, 19} For instance, the amplitude of the accommodative vergence movements in Fig. 3 equaled 4.2° in the covered eye and 1.2° in the viewing eye for both convergence and divergence. The binocular saccade, due to the retinal error in the viewing eye, moves the fovea of the dominant eye close to the new target. Both qualitatively and quantitatively, the responses from the control subjects' monocular tracking were similar to those recorded in our patients under binocular viewing conditions

(Figs. 1, b, and 2). Each contained unequal vergence; the smaller amplitude occurred in the viewing eye for the control subject and in the dominant eye for the patients; and finally, each used a saccade to bring the fovea of the dominant eye near the new target.

When patients with strabismus and/or amblyopia were monocularly occluded, so that only the dominant eye viewed the symmetrically positioned targets, responses agreed both qualitatively and quantitatively with the symmetric vergence responses from these patients under binocular viewing conditions. As with the control subjects, blocking of one eye caused accommodation to

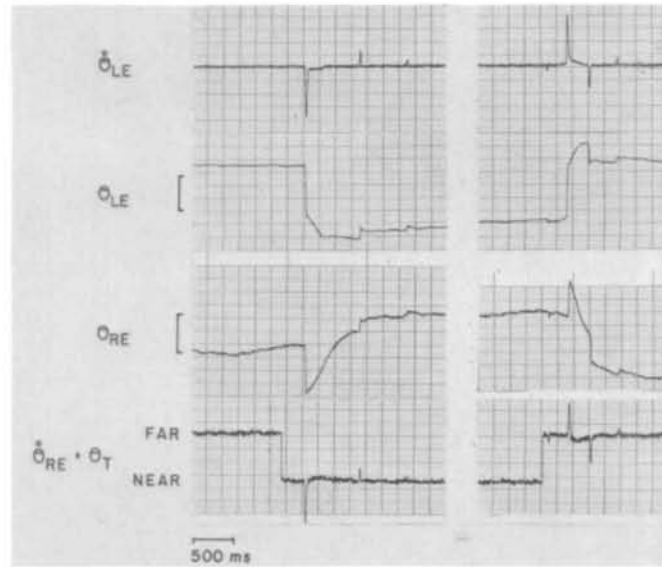


Fig. 3. Monocular tracking of midline targets with dominant eye. Normal Control Subject B. L. with left eye occluded. Note vergence occurring predominantly in occluded eye; viewing eye saccade is used to foveate new target.

drive vergence, producing unequal vergence amplitudes. The monocular retinal error produced by the target change caused a binocular saccade placing the dominant eye on the new target.

Monocular line of sight targets. To study the ability of these patients to make normal accommodative vergence responses, the targets were carefully aligned along the visual axis of the dominant eye with the fellow eye occluded. (the Müller experiment).¹⁹ Under this condition, a large accommodative vergence response occurs in the covered non-dominant eye.¹⁹ We have recently shown that besides the large vergence in the covered eye, the viewing eye makes small vergence responses approximately 12% of the amplitude of that measured in the covered eye.⁹ A clear example of this accommodative vergence movement is seen in the responses from Control Subject B. L. (Fig. 4, a). In the divergence response, the small vergence in the viewing eye equaled 25% of that found in the covered eye. The small corrective saccades were used to keep the viewing eye on the target and thus counteracted the small vergence driving the viewing eye away from the target. The responses from our patients

under these conditions appeared similar to the accommodative vergence responses found in normals. Typical accommodative vergence responses from our patients are shown in Fig. 4, b. This figure shows the eye movement normal characteristics of accommodative vergence: smaller amplitude vergence in the viewing eye (25% of the amplitude in the covered eye) and corrective eye movement patterns.⁹ In general, accommodative vergence *with the dominant eye viewing* was normal in all patients.

Special cases. Neither degree of strabismus nor grade of amblyopia in patients with constant strabismus amblyopia had any effect on the responses to the symmetric vergence stimuli. Patients with small-angle strabismus and deep amblyopia (B. B.) produced symmetric vergence responses similar to those of patients who had mild amblyopia and small-angle strabismus (B. S.). Furthermore, the presence of ARC, as found for Patient B. S. but not B. B., did not alter the basic response.

Within our group of patients, three were successfully treated for amblyopia or strabismus. Patient B. W. received orthoptics ther-

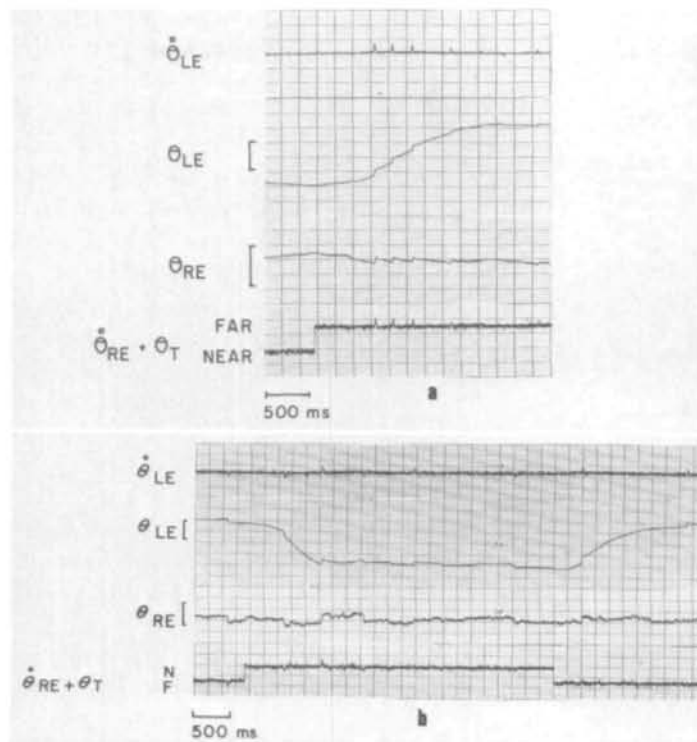


Fig. 4. Accommodative vergence with dominant eye viewing. a, Normal Control Subject B. L., with left eye occluded. Note vergence occurring primarily in occluded eye and small vergence in viewing eye, similar to that recently reported in other normal subjects.⁹ b, Patient B. N. having intermittent strabismus without amblyopia. Accommodative vergence shows normal dynamical response characteristics.

apy for amblyopia and eccentric fixation in the left eye. After training, his visual acuity increased from 20/110 to 20/20, and his eccentric fixation reduced from 2 prism diopters (PD) to zero. His vergence movements, recorded shortly after termination of orthoptics treatment, contained the same characteristic abnormal vergence response recorded in most of our patients. Thus, even after normalization of visual acuity and centralization of fixation, normal disparity vergence responses were never recorded in this former amblyope. Interestingly, some other oculomotor findings such as saccadic latency remained abnormal in this patient during and subsequent to successful amblyopia therapy.²⁰⁻²²

Patients with a history of strabismus as a child and surgical correction to reduce the strabismus were also included in our sample and showed the typical abnormal vergence

responses. Patient J. B. who now has an exophoria was operated on at age 8 to correct a squint of his left eye. His symmetric vergence responses were similar to those of the other patients in our study having strabismus but who were not surgically corrected. However, another patient, J. W., who had an esotropia surgically corrected at age 3 and presently has an esophoria, had intermittent episodes of normal convergence interspersed with more frequent abnormal responses.

Non-Hering's law saccades during vergence. During the analysis of vergence responses from both patients and control subjects, we found that saccades which occurred during vergence were often unequal in each eye. Fig. 5 shows symmetric vergence responses that contained saccades during disparity vergence from the control subjects. Although the vergences in each eye were approximately equal, the saccades were

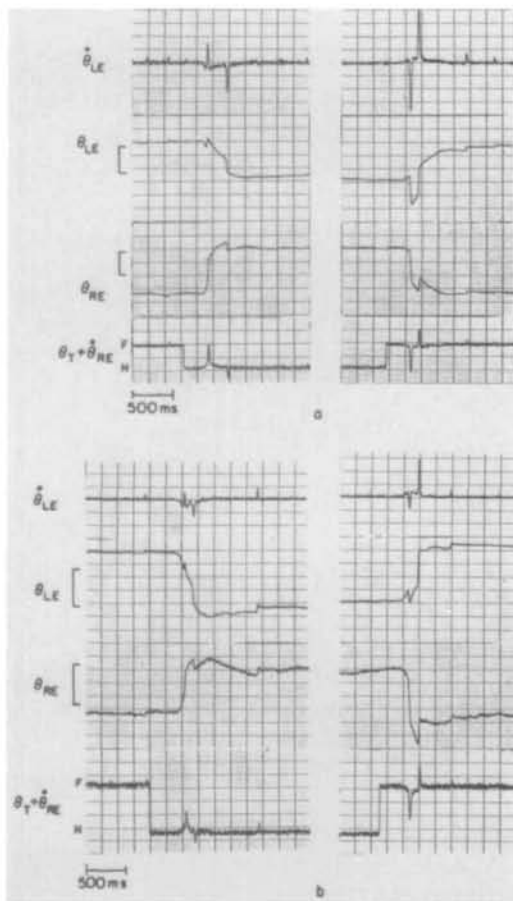


Fig. 5. Non-Hering's law saccades in normal control subjects. **a**, Subject A. D. In left record, note 0.6° saccade in left eye and 2.0° saccade in right eye occurring early in convergence response. Similar markedly unequal saccades found early in divergence responses (right record) of same subject; yet observe similar size of saccades following completion of divergence, clearly demonstrating that calibrations are accurate. **b**, Subject B. L. As found in Subject A. D., markedly unequal saccades occur during vergence response but not during fixation periods following, or prior to, the large vergence responses.

markedly unequal. For example, the saccadic pair 60 msec after the start of convergence in Fig. 5 *a* (A. D.), had amplitudes of 3.1° and 0.8° for the right and left eyes, respectively. The smaller saccade measured 26% of the amplitude of the larger saccade. The next saccadic pair was not as dramatically unequal. Also, the smaller saccade was now in the

right eye, whereas it appeared in the left eye for the previous pair. This same pattern was repeated in the divergence response. The saccadic properties found during vergence in all subjects were best illustrated by the responses of control subject B. L. (Fig. 5, *b*). The divergence response showed dramatic differences in the amplitudes of the first saccadic pair during vergence, with relative saccadic amplitude equaling 31%. For the first pair, the smaller saccade was in the left eye. The following saccadic pair was not as unequal as the first, and relative amplitude equaled 52%. Also, the smaller saccade now appeared in the right eye. For all subjects the smaller saccade always occurred opposite to the direction of the vergence movement of that eye, and the amount of inequality was generally larger near the start of the vergence than at the end.

Looking back through the responses of our patients, one finds that several showed these two characteristics. As each saccadic pair is discussed, notice that the smaller saccade opposes the vergence movement. During the first 150 msec of the vergence, the difference in the amplitudes of the two saccades was usually greatest. In Fig. 2, *a* (J. K.), the saccade at the beginning of the divergence had 44% of the amplitude of the fellow eye saccade. As the saccades occurred later in the vergence, the amplitude differences were not as great. In Fig. 1, *b* (B. N.), the saccade 600 msec after the start of the divergence had relative amplitude of 67%. In Fig. 2, *b* (S. H.), the smaller saccade 300 msec after the start of the divergence equaled 60% of the amplitude of the saccade of the other eye. Finally, saccades following completion of the vergence response were equal. For example, saccades after the convergence in Fig. 5, *a*, prior to the vergence in Fig. 2, *a*, and between the vergence responses in Fig. 1, *b*, were all equal. These equal saccades occurring after the vergences provide additional evidence that saccades are indeed unequal and are not due to a nonlinearity in the eye-movement recording system.

To summarize the non-Hering's law saccade result, the relative saccadic amplitudes

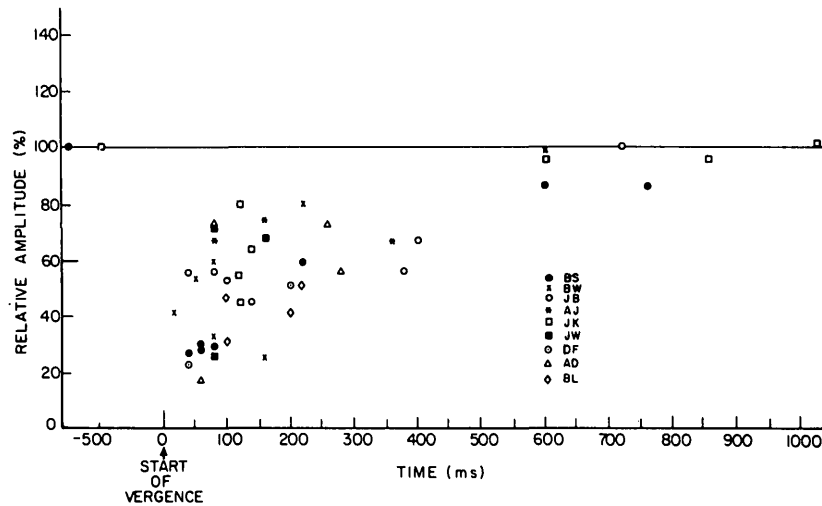


Fig. 6. Relative amplitude of saccades in each eye as a function of time during vergence response for seven patients and two control subjects. Plot clearly shows reduction in non-Hering's law saccades as they occur later in the vergence movement.

Table II. Percent relative vergence

Subject	Symmetric vergence targets (binocular)	Symmetric vergence targets (nondominant eye covered)	Accommodative vergence along dominant eye (nondominant eye covered)
Normal control subjects:			
B. L.	92.1% ± 3	26.0% ± 3	20.0% ± 5
A. D.	89.0% ± 8	17.0% ± 5	14.5% ± 9
Constant strabismus amblyopia:			
D. F.	16.0% ± 4	15.0% ± 3	13.0% ± 5
Intermittent strabismus without amblyopia:			
B. N.	7.6% ± 2	8.5% ± 4	8.0% ± 1
Amblyopia without strabismus:			
S. H.	7.0% ± 2	9.0% ± 1	7.5% ± 3
Former strabismus patient:			
J. B.	11.0% ± 5	5.3% ± 2	6.0% ± 2

from all subjects during vergence are plotted in Fig. 6. The ordinate represents percent relative amplitude, and the abscissa is time before and after the start of the vergence movement. The relative amplitude is defined as the ratio, in percent, of the smaller saccade to the larger saccade. The solid line at 100% represents the ratio expected if equal amplitude saccades occurred in each eye. The graph shows that most saccadic pairs during vergence had relative amplitudes of 60% or

lower. Furthermore, the lowest relative amplitudes occurred early in the vergence and then slowly increased until, at about 700 msec, both saccades were approximately equal. Also notice that saccades before the vergence movement were approximately equal; it is only during the vergence movement that unequal saccades were found. The plot also shows that not all saccades that occurred at a particular time after the start of the vergence were reduced by the same

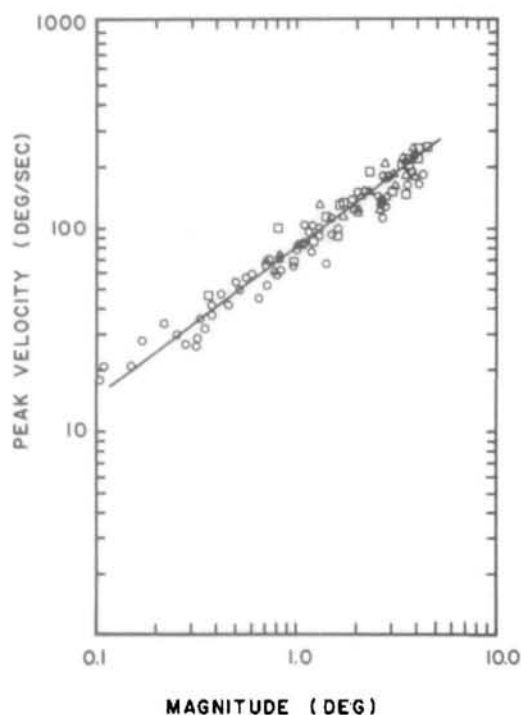


Fig. 7. Main sequence for eye movements used to identify normal saccades. The solid line represents locus of points for normal saccades. Symbols represent saccades from normal subjects and Patients J. K. and B. N., during the vergence. The circles, squares, and triangles represent Control Subject B. L. and Patients J. K. and B. N., respectively. Saccades cluster around the main sequence line, indicating that despite the inequality of the saccades they remain normal.

amount. Some of these differences were due to intersubject variability, as can be seen by the placement of the different symbols on the graph. Still, some intrasubject variability was evident when data from an individual subject were examined. Despite this scatter, the saccades were clearly unequal during the vergence in both subjects and patients. Although the gradual increases in saccadic equality have been plotted as a function of the timing between the saccade and vergence, it may also be related to the velocity of the ongoing vergence and the saccade. Further experiments will be needed to clarify this relationship.

An analysis of these unequal saccades reveals that they all have normal main se-

quence²³ peak velocity–amplitude characteristics. The peak velocity–amplitude plot for saccades for normals is represented by the solid line in Fig. 7. The cluster of symbols around the normal saccadic line indicates that our patients' saccades during vergence movements had normal dynamics.

Discussion

Absence of disparity vergence. Normal disparity vergence eye movements, induced by fixating near and far midline targets, are characterized by smooth, equal, disjunctive movements of both eyes. The eye movements of our control subject (Fig. 1, *a*) illustrate this characteristic response, well-known in the literature on vergence eye movements.^{14–18} In contrast, under binocular viewing conditions where disparity vergence should be operating, most patients displayed a conspicuous lack of normal disparity vergence movements. A qualitative comparison of the responses of the patients and the control subjects supports this hypothesis.

Possible mechanisms blocking disparity vergence. The absence of disparity vergence under binocular viewing conditions indicates that a disparity blocking mechanism is operating in all groups of patients. Suppression is the most likely condition. Strabismus patients with deviations greater than 10 PD, as found in many of our patients, generally use suppression to eliminate diplopia and confusion caused by the strabismus.^{24–28} The size of the suppression scotoma has been found to be a function of the angle of deviation, encompassing the region between and including the fovea and the diplopia point.^{24, 25} Suppression is also commonly found in patients with amblyopia only and may explain the lack of disparity vergence found in some of our amblyopic patients. Of particular interest is the intermittent nature of the vergence recorded in patients having amblyopia without strabismus. For example, Patient S. H. at times made normal disparity vergence, and L. T. always did so. These results, together with the absence of normal disparity vergence eye movements in strabismus patients with and without amblyopia, suggest

that strabismus has a stronger effect on the disparity vergence system than does amblyopia.

Some of our patients with strabismus also had ARC. Interestingly, these patients also showed an absence of disparity vergence. Jampolsky²⁵ showed that suppression characteristics are dependent on stimuli conditions, whereas the results of Bagolini²⁸ suggest that when patients with ARC are allowed to view freely, the suppression found is usually minimal. Bagolini²⁹ has established, by measuring haplophoria horopters, a markedly increased Panum's area in such patients. Indeed, plasticity of Panum's area in normal subjects is dependent upon the nature of the stimuli and the state of the feedback control system, as has been demonstrated by Fender and Julesz³⁰ and Diner.³¹ Perhaps an expanded Panum's area could eliminate the need for vergence and thereby provide a possible mechanism underlying the absence of disparity vergence in our patients with ARC.

For our patients J. B. and J. W. who have a history of strabismus, and B. W. who has a history of amblyopia, the lack of disparity vergence movements suggests some connection between their former abnormal clinical condition and their vergence responses. Here, the important studies of single cortical units in animals with experimental strabismus and amblyopia may provide important clues toward the understanding of human strabismus and amblyopia. These reports show that if strabismus and amblyopia are produced early in life, the number of cortical cells that respond to disparity or binocular stimuli is much less than that usually found in normal animals.³²⁻³⁶ If this abnormal visual experience is continued throughout the animal's "sensitive period," the response patterns of the cortical cells are difficult to modify later.³⁷ Perhaps, in the case of our Patients J. B., J. W., and B. W., their abnormal early visual experience may have affected cells that respond to disparity to such an extent that these cells no longer respond normally to disparity information. This also may be an additional mechanism operating in patients who still have strabismus and/or amblyopia.

If, in the future, animal experiments involving induced strabismus and/or amblyopia vergence eye movements were measured, this would provide an additional criterion for their being adequate models of human strabismus and amblyopia and would also correlate these hypotheses with neurophysiological experiments.

Accommodative vergence. Several pieces of evidence strongly suggest that these unequal vergence responses found in our patients are not disparity vergence but rather accommodative vergence. Accommodative vergence studies on normal subjects show an asymmetry in the amplitudes of the vergence in each eye. Müller¹⁹ first described the large vergence in the covered eye, and we⁹ have recently shown that the viewing eye verges approximately 12% of the amplitude measured in the covered eye. The responses of Control Subject A. D. (Fig. 4, *a*) demonstrate this characteristic accommodative vergence movement. Similar characteristics are also found in the binocular viewing response of our patients indicating that these unequal vergence movements are accommodative vergence. A test of this hypothesis, performed by covering the patient's nondominant eye, showed that the response under monocular conditions contained the same general characteristics as found in these same patients under binocular viewing conditions. Furthermore, when one eye of a normal subject was occluded, responses were similar to those of patients under binocular viewing conditions. Finally, the accommodative vergence responses of our patients showed normal characteristics similar to the characteristics of our control subjects. Table II summarizes the relation between the vergence amplitudes in each eye for control subjects and one patient from each category under binocular and monocular conditions. There is a clear difference in the relative amplitudes during binocular conditions between the control subjects and the patients. Under monocular conditions, the controls show a large difference between the monocular and the binocular condition, but patients show little difference in relative vergence under each

condition. Also the relative vergences under both monocular and binocular conditions for patients are similar to those of the controls under monocular conditions. Therefore we conclude that patients in our study made normal accommodative vergence and not disparity vergence under binocular viewing conditions. Blake et al.³⁸ speculated that convergence changes observed in his kittens reared with alternating monocular occlusion might be due to binocular disparity, changes in image size, or changes in accommodation; in our human subjects we find that accommodative vergence is the principal mechanism responsible for the vergence movement.

Non-Hering's law saccades. One of the most interesting new findings of our study was the presence of non-Hering's law saccades during vergence. Non-Hering's law saccades were present in at least 85% of the vergence movements found in all diagnostic groups of patients. We were alerted to this possibility because of our previous finding of non-Hering's law saccades during accommodative vergence in normal subjects.⁹ As pointed out in Results, the smaller saccade opposed direction of the ongoing vergence; the direction of the saccades is determined by the retinal error in the dominant eye. The properties of a smaller saccade opposing the vergence and a smaller vergence in the dominant eye combine, so that the inequalities contribute to the amplitudes of the ongoing convergence or divergence. For example, in response to convergence stimuli, a patient with strabismus of the left eye will use a saccade to place the dominant right eye onto the near target. A leftward saccade in both eyes will move the right eye on the target and the left eye away from the target. The smaller saccade opposing the vergence causes the left eye to move less than the right; the result is that both eyes are converged more after the saccade than before. The addition of a larger vergence in the left eye than the right keeps the dominant right eye on the target while moving the left eye towards the target. Thus the saccade carries about half the burden of the vergence movement, and the accommodative vergence does the other half.

The inequalities of these saccades are not restricted to patients,^{9, 39} since non-Hering's law saccades appear during vergence movements in normals (Fig. 5). In control subjects, the saccades occur sparsely under binocular conditions, usually during divergence. In patients, the saccades are present in almost all vergences. Only when the control subjects occlude one eye does the saccade occur with the regularity of that found in patients. In the control subjects, the saccades are due to the monocular retinal error in the viewing eye. The occurrence of a similar function in most patients may be construed as evidence for suppression of the nondominant eye in these patients.

Possible mechanisms for non-Hering's law saccades. Knowledge of the fine structure of saccades may provide a clue to the underlying physiological mechanism responsible for production of unequal saccades. We have ruled out simple linear summation of the saccade with the vergence movement. If simple linear summation of saccadic and vergence positions were responsible for a change in the saccadic magnitudes, then the amplitude differences should be equal to the additional vergence amplitude the eye moved during the saccade. Compensating the saccadic amplitudes for the vergence during the saccade should yield equal saccadic pairs. However, saccades compensated for the vergence movement still have amplitudes that are 70% of their uncompensated value. This small reduction is due to the short duration of the saccade, circa 25 msec, and the slow velocity of the vergence, circa 20°/sec. The combination results in little additional eye movement. In addition, we chose to analyze saccades that are large enough so that the amount of additional amplitude due to the vergence is insignificant.

Nonlinear summation in the muscle or in the motoneuronal pool is possible but unlikely, since the smaller saccades have shorter duration than the larger saccades occurring concomitantly in the other eye and thus may be already programmed to be smaller at a higher interneuronal level. Alternatively, it may be a complex interaction

of muscle forces, viscosities, elasticities, accelerations, velocities, and positions separately controlled or influenced by vergence and saccadic neural control signals. In addition, the main sequence analysis shows that these saccades are not abnormally fast or slow with respect to saccades made free from vergence influences. The peak velocity and amplitudes correspond well with the normal main sequence measurements. Therefore any mechanism which will reduce or enhance these saccades must equally affect the peak velocity as well as the amplitude. Further experimental, simulation, and neurological studies will be necessary to clarify the generation of the non-Hering's law saccades.

Summary. Vergence eye movements in most patients with strabismus and/or amblyopia are restricted to accommodative vergence movements. The characteristic response to disparity produced by targets at different distances involves binocular saccades which fixate the dominant eye on the target together with an accommodative vergence. Saccades of both patients and control subjects that occur during vergence are unequal, with the saccade moving against vergence being the smaller. Main sequence analysis shows that both equal and unequal saccades have normal peak velocity-magnitude relationship. Strabismus appears to have a stronger disruptive effect on normal disparity vergence than does amblyopia; surgery and orthoptics to relieve strabismus and amblyopia have mixed effects on vergence responses.

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