1040-5488/03/8011-0764/0 VOL. 80, NO. 11, PP. 764–771
OPTOMETRY AND VISION SCIENCE

ORIGINAL ARTICLE

Errors of Binocular Fixation are Common in Normal Subjects during Natural Conditions

ELAINE D. CORNELL, MA, HAMISH G. MACDOUGALL, PhD, JOHN PREDEBON, PhD, and IAN S. CURTHOYS, PhD

Vestibular Research Laboratory of the Department of Psychology, University of Sydney, Sydney, Australia

ABSTRACT: *Purpose.* To investigate the accuracy of fixation after symmetrical vergence eye movements along the midline during natural full-field viewing conditions using a video method of eye position measurement. *Methods.* The accuracy of binocular fixation after symmetrical vergence eye movements during natural conditions was measured on 29 young adults using a precise head-mounted video eye movement measuring system. All subjects had normal binocular vision and good visual acuity. Measurements were taken for both near and far fixation after vergence changes of 5°, 10°, and 15° using three rates of change, approximately 0.25, 0.5, and 1 Hz. *Results.* The amplitude of the vergence movement tended to be hypometric, resulting in underconvergence for near fixations, and overconvergence for distance fixation. For far fixations, most errors (82%) were from −120 to +120 min arc, and for near, most errors (85%) were from −30 to +120 min arc. For far fixations, there was a significant effect of the size of vergence change ($F_{1,28} = 61.8$; $p < 0.001$), the rate of change ($F_{1,28} = 7.08$; $p = 0.013$), and the interaction between these two factors ($F_{1,28} = 7.17$; $p = 0.012$) on resulting errors, with the eyes showing greater overconvergence on the target for the larger and faster fixation changes. For near fixations, there was a significant effect ($F_{1,28} = 15.9$; $p < 0.001$) for the angle of change with the faster vergence changes producing relatively more convergence, thus reducing the mean vergence error. No subject reported diplopia during any conditions despite our measures showing vergence errors of up to 5°. *Conclusions.* Vergence errors of up to ±2°, without diplopia, were common in subjects with normal binocular single vision. Errors of 5° were rare but present. In all, the largest number of errors occurred as a failure of divergence for far fixations, consistent with previous studies that have suggested differences in the neural control of pathways for convergence and divergence, or possibly caused by differences in the anatomical properties of the medial and lateral rectus muscles and their associated fascia. The absence of diplopia during the period of fixation could only be partly associated with the visual suppression associated with vergence eye movements that has been reported by others because it was still present after the vergence movement was completed. The natural viewing conditions in this study that included a full visual field and multiple disparities may have contributed to this effect. (Optom Vis Sci 2003;80: 764–771)

Key Words: binocular vision, convergence, divergence, vergence eye movements, diplopia

Horizontal vergence movements (convergence and divergence) allow for binocular fixation on near or far targets. These movements are characterized by a fast-acting mechanism that aligns the eyes in response to retinal image disparity (phasic response) and a slow acting mechanism (tonic response) that responds to the output of the fast control mechanism.[1] The fast response is characterized by a period of peak velocity and duration that increases systematically with vergence amplitude[2] but with a frequent addition of a corrective saccade before final fixation, even for stimuli eliciting pure symmetrical vergence.[3]

Studies of fixation disparity have been well documented.[1, 4–7] Schor[6] considers it to be a steady-state error of a negative feedback system that increases the stability of the slow fusional vergence system by providing a stimulus to maintain steady-state convergence and prevent its decay. In studies of fixation disparity, a haploscopic device is frequently used, with the subject using subjective judgment of the alignment of nonius markers to determine the projection of retinal areas during various conditions of fusion demand. These techniques usually demonstrate binocular fixation errors of up to 20 min arc. However, measurements of such errors are usually larger if the position of the eyes is also measured objectively,[8–11] casting doubt on the accuracy of subjective measures of fixation disparity to indicate the precise alignment of the eyes.

Experiments carried out in a more natural environment, especially those that use objective measures, and with the head unrestrained, often reveal large vergence errors. These experiments usually involve stimulation of the fast (phasic) vergence system.

Erkelens et al.[2, 12] measured vergence eye movements of subjects in free space during varying conditions and reported errors of around 1° when the target velocity was up to 20°/s, but these errors rose sharply to 4° to 6° for faster velocities of 70° to 110°/s. Despite these large vergence errors and the noncorrespondence they imply, observers did not report diplopia.

Collewijn et al.,[3] using a scleral coil technique, but with the head restrained, reported that some subjects showed "ambiguous" vergence movements that achieved only half the required vergence change after 5° or 10° symmetrical vergence changes. Epelboim et al.,[13–16] in similar experiments, but with the head unrestrained, reported errors in "gaze shifts" (i.e., lateral errors). Although vergence errors were not analyzed in these reports, their representations of the recorded binocular eye movements from that study (http://brissweb.umd.edu/eyemove/starteyemove.html) show significant vergence errors. In a subsequent report from the same laboratory, Malinov et al.[17] noted that subjects "underverged" by 25% to 35% during some tasks. Calculations from the target distances reported from that study indicate that these vergence errors ranged from approximately 1.5° to 3°.

What is of particular interest in these "free space" studies is that none deliberately induced the vergence demand that is usually an integral component in fixation disparity experiments. The various stimuli to vergence, accommodation disparity and proximity, were acting in harmony, unless the subjects had a significant heterophoria. Yet these conditions were those in which objective measures of eye position showed significantly large vergence errors. However, many such studies use only a relatively small number of subjects who are often experienced in eye movement research and aware of the expected outcomes. Scleral search coil measurements can be affected by slippage of the coils[18] and other factors that may affect the kinematics of eye movements[19] possibly resulting in artifactual measurements of eye position and resulting apparent vergence errors.

The purpose of this study was to investigate the following during conditions as natural as possible in a group of normal young adults who were naive to eye-movement research:

- the accuracy of vergence eye movements for both near and far fixations;
- the effect of the size of vergence change and the rate of change on any vergence errors using a precise video image processing method of measuring binocular eye positions.

METHODS

The protocol for the study was approved by the Human Ethics Committee of the University of Sydney and followed the tenets of the Declaration of Helsinki.

Subjects

Twenty-nine subjects aged between 18 and 27 years were studied after informed consent. All had 20/20 vision in each eye (either uncorrected or corrected with contact lenses) and were within 2Δ of orthophoria for far fixation and 8Δ of exophoria to 4Δ of esophoria for near fixation as measured by the alternate prism cover test. All had stereopsis of at least 60 sec arc on the Wirt stereopsis test, full ocular rotations, and a convergence nearpoint of 8 cm or better.

The video eye movement system (VidEyeO) used an IBM compatible PC (Intel P3 cpu at 600 MHz, 128 Mb Ram) that incorporated two analog monochrome video acquisition cards (National Instruments PCI NI-IMAQ 1408) that were hardware synchronized using the real-time systems integration bus.

The video headset consisted of an adjustable headband that held an alloy frame on which two monochrome infrared-sensitive CCTV video surveillance cameras (480 H-Lines SONY HAD CCD and SONY Chipset) were mounted. Two half silvered "hot mirrors" (WBHM/Glass/1 Side CT, OCLI, Santa Rosa, CA) reflected the infrared image of the eye to the cameras that were placed off to each side to afford the subject an unobstructed view of the fully lit laboratory.

Each eye was illuminated from above and below by two infrared LED emitters that were invisible to the subject; infrared pass filters (~730 nanometers wavelength film 0.1 mm flexible) on the camera lenses prevented ambient light from affecting the image of the eye.

Synchronized video images of both eyes were analyzed using in-house software written for the project. This software was written in a development environment (LabView) and used a library of image analysis functions (Vision), both from National Instruments (Austin, TX).

The video images of each eye were adjusted to give maximum contrast that clearly identified each pupil. Horizontal and vertical eye positions to a resolution of 0.1° could then be calculated by tracking the center of mass of the largest black object (the pupil) in each binary (thresholded) video image and converting its position into gaze angles using geometric transformations and calibration procedures that we have previously published.[20, 21] The sampling rate was 17 Hz, which although relatively low, permitted a highly accurate binocular measurement of the eye position during the fixation period after the vergence movement (Fig. 1). The dynamic properties of the eye movements, which showed evidence of combined saccades, vergence, and, at times, corrective movements, were not analyzed in this study because the aim was to measure the accuracy of eye position during the fixations. During recording sessions, the video images tracked by the system could be viewed by the examiner, and recordings were deleted if other ocular landmarks (such as the eyelids) interfered with the pupil measurement. Vergence was calculated as the difference between the gaze angles for the two eyes.

Because the position of the eye was determined by the center of mass of the pupil, there was a possibility that this could be affected by idiosyncratic or asymmetrical changes in pupil size. Yang et al.[22] have demonstrated that the pupil center shifts approximately 0.133 mm temporally between mesopic and photopic conditions. During development of the VidEyeO system, this possibility was tested on four subjects using frequency analysis to separate the

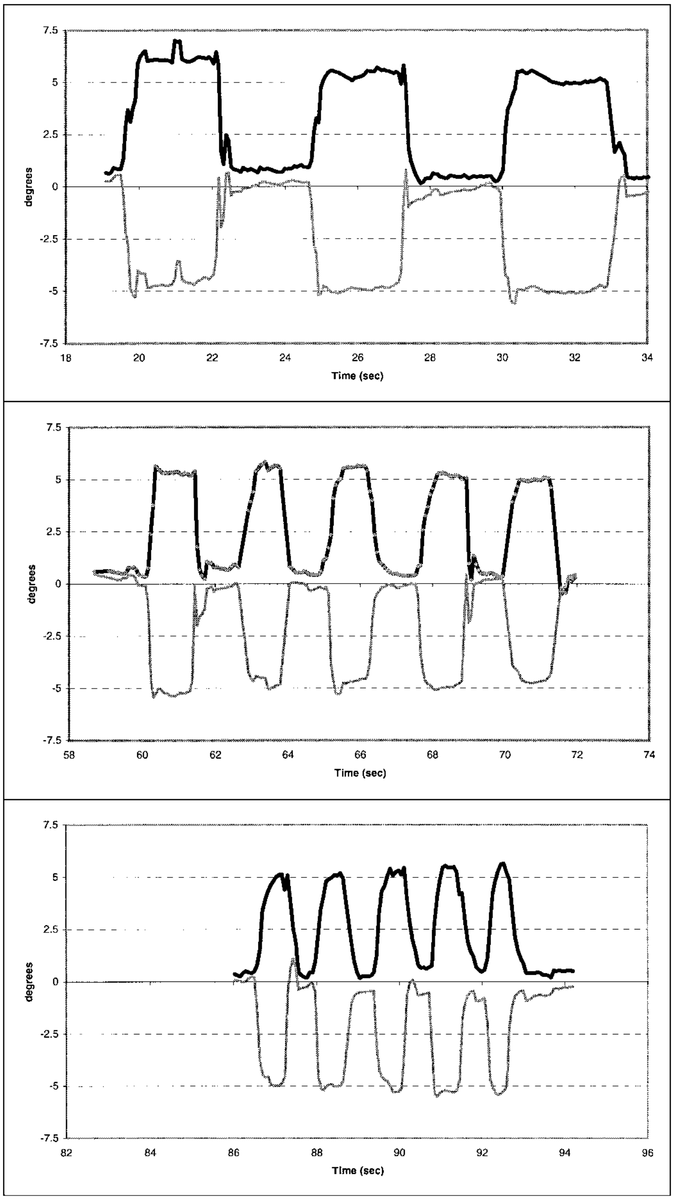

FIGURE 1.

Typical traces of binocular eye positions for one subject to targets set at 200 cm (far) and 30 cm (near), requiring a 10° vergence movement. Rate of change is approximately 0.25 Hz (top), 0.5 Hz (middle), and 1 Hz (bottom). Upward deflections of the right eye (black line) and downward deflection of the left eye (gray line) represent convergence. The failure of the eyes to fully diverge to the far target and the frequent overconvergence on the near target can be seen.

effect of pupil dilation from other sources of variability. The results showed an absence of any systematic interaction between pupil dilation induced by sinusoidal modulation of ambient lighting and horizontal and vertical position measurements. For this study, recordings from each subject were also individually analyzed to determine whether there was any apparent effect of change in pupil size on the measured horizontal position of the eye (see Results).

Calibration

To determine errors of binocular fixation, the assumption was made that careful monocular fixations on detailed targets at both far and near represented foveal fixation and that any variation from these positions during conditions of binocular vision represented a vergence error. This assumption is similar to that made by Simonsz and Bour[10] in a study of foveal alignment during fixation disparity. Calibration was therefore carried out monocularly with each eye before each recording. The geometric transformations that formed part of the software gave highly linear and stable two-point calibrations that were confirmed in a preliminary study. The subject first fixated carefully with one eye on the far target for 5 s, and the resulting recording was then observed by the experimenter and was accepted only if it demonstrated steady fixation without any blinks. Fixations that showed any blinks or small saccadic movements could be deleted and the process repeated. The mean value for this fixation was then automatically computed. The process was repeated for the near target, and the entire sequence was repeated for the other eye.

To overcome any artifacts that may be caused by asymmetric pupillary constriction associated with vergence during the test, calibration was carried out on the near and far targets rather than on laterally displaced targets. Any small lateral differences between the movement of each eye that may have occurred if the near target was not precisely on the midline would not have affected the overall measure of vergence because this was calculated as the sum of the right and left eye positions.

Experimental Protocol

Initially, two experiments were carried out to evaluate any effect of the distance of the far target, that is, whether the need to fully relax convergence on a far distance target would have any effect on the resulting binocular fixation. In the first experiment, the far target was a chimney approximately 200 m away, seen through a window. The near targets were set at 71, 34.4, and 23.5 cm, requiring 5°, 10°, and 15° of vergence change. For the second experiment the far target was set at 2 m from the subject. The proximal targets were set at 52.5, 30, and 21 cm, requiring 5°, 10°, and 15° vergence change (6.8°, 11.8°, and 16.8° of absolute convergence on the near target). A pupillary distance of 62 mm was assumed to define these positions. Because errors were calculated from these calibrated distances, normal variations in pupillary distance would have a negligible effect of resulting measurement of any error.

Results were only analyzed from subjects whose recordings were acceptable during all conditions, that is, they were not affected by the lids or eyelashes or apparent movement of the head.

In both experiments, viewing conditions were kept as normal as possible; however, it is acknowledged that the experimental situation that involved a head-mounted recording device, eye movements initiated by instruction, and the use of a bite bar did not provide a completely natural situation. In this study, the near target was a black and white image of a star (13 mm^2) with a central cross (5 mm^2) that could be moved up or down a fine rod to be at eye level. For the first experiment, a distant roof line was viewed through a window (90 × 240 cm), and the far target, the chimney, seen approximately through the middle of the window, was clearly visible against the sky. For the second experiment, the far target was a star similar to the near targets (50 mm^2; central cross 15 mm^2). The chair height and head rest were set so that the targets were along the subject's midline at eye level, thus requiring horizontal eye movements only. There was no attempt to control any of the varied peripheral visual stimuli in the laboratory, however a bite bar was used to ensure that the distance of the fixation targets from the eyes did not vary during the experiment.

For each subject, three data sets were obtained, each represented a specific size of vergence change (5°, 10°, and 15°) during which the rate of change was varied. For each rate of change, three or four changes of fixation on each of the near and far targets were recorded. The order of both angle of change and rate of change was randomized between subjects.

Initially, a metronome was used to direct the subject when to change fixation. However, this produced anticipatory eye movements and confusion when the subject got out of step with the metronome beat. Better results were achieved if the experimenter, observing the subject's eyes on the video monitor, gave verbal instructions by counting aloud at a rate of approximately 0.25 Hz for each fixation during the "slow" changes (2 s for each fixation at far and near), 0.5 Hz for the "medium" changes (1 s for each fixation at far and near), and 1 Hz for the "fast" changes (0.5 s for each fixation at far and near). This observation and control by the examiner allowed for corrections and repeated movements if necessary. All measurements used in this report used this verbal signaling method. Subjects were asked to report diplopia if this occurred.

The resulting recordings were examined. Although there was a relatively slow sampling rate, each vergence movement could be recognized by a fast vergence movement that often included a small conjugate corrective movement, followed by a relatively stable phase during fixation (Fig. 1). The position of each eye during the fixation period was determined subjectively. Although the period of the initial glissade or compensatory saccade was excluded from the measurement, small square-wave jerks during the fixation period were included because these conjugate movements did not affect the measure of vergence. However, movements that were affected by blinks or were clearly abnormal were excluded. In most cases, three or four fixations were suitable for analysis for each rate of change. The software used in the analysis gave the mean and standard deviation of the horizontal position for each eye and the number of data points for each fixation. The measured value of the position of each eye was subtracted from the calibrated value, and the resulting vergence errors were expressed in minutes of arc. Because there were very small standard deviations (usually <10 min arc), the pooled mean measures of vergence for each condition and for each subject were used for further analysis. The significance level was set at 0.05.

RESULTS

There were no statistically significant differences between any of the nine conditions (three changes of angle at three rates of change) in each of the two experiments, so the data from the two experiments were pooled.

Inspection of the recordings indicated that there was, as expected, a moderate relationship between pupil size and fixation distance. However, the onset of the vergence movement usually did not coincide with the onset of pupillary constriction or dilation, and there were many fluctuations of pupil size that were not associated with change in the measured position of the eye (Fig. 2). These observations indicate that the measurements of horizontal eye position using our system were not directly affected by changes in pupil size. A further testing of this assumption involved calculating correlation coefficients of pupil size with eye position on each eye of all subjects Twenty-five subjects (86%) had r values <0.3 in one or both eyes; of these, 16 (64%) subjects had r values that were <0.1 in each eye. Fig. 2 shows a sample recording of the subject (LK) showing the highest correlations ($r = 0.42$ in both eyes). Comparison of the change in the horizontal eye position and pupil area in this subject during 20 s and the detail of one cycle of far and near fixation demonstrates that fluctuations in pupil size did not influence the measurement of eye position.

The distribution of all vergence errors is shown in Fig. 3 and descriptive data are shown in Table 1. For far fixation, vergence errors were between −323 and +180 min arc. The mean value was −29.7 min arc, with a standard deviation of 94 min arc and a median value of −9.6 min arc. For near fixation, vergence errors were between −70 and +232 min arc. The mean value was +38 min arc, with a standard deviation of 50.5 min arc and a median value of 34 min arc. Although these data demonstrate considerable variation in the results between subjects, especially for near fixation, the recordings for individual subjects showed little variation.

The overall amplitude of the vergence movements tended to be hypometric, resulting in underconvergence on the near target and overconvergence (or underdivergence) on the far target (Fig. 4). This effect was greatest for the large and fast movements. Analysis of variance (planned orthogonal contrasts) using the vergence error data confirmed a significant effect for far fixations of both the size of vergence change ($F_{1,28} = 61.8$; $p < 0.001$), the rate of change ($F_{1,28} = 7.08$; $p = 0.013$), and the interaction between these two factors ($F_{1,28} = 7.17$; $p = 0.012$) on resulting errors, with the eyes showing greater overconvergence on the target for the larger and faster fixation changes. For near fixations, there was a significant effect ($F_{1,28} = 15.9$; $p < 0.001$) for the angle of change, with the larger vergence changes producing relatively more convergence, thus reducing the mean vergence error. There was no significant effect for the rate of change on errors for near fixation. Although the mean values suggest similar effects as those found for far, the larger variability in the near errors may have affected this conclusion.

DISCUSSION

Errors of between −323 and +232 min arc were found, but most were within 120 min arc. These limits are similar to those found in similar free space experiments by Erkelens et al.,[2] Collewijn et al.,[3] and Malinov et al.[17] when subjects made voluntary shifts between stationary targets. It is of interest that these values are similar to the 3° limits of "dimpling" of the horopter during forced vergence as reported by Fogt and Jones,[23] although that study only demonstrated dimpling of the horopter in relation to stimulation of a small, central target.

The highest average errors occurred for the large and fast fixation changes to a far target, that is, after a divergence movement. Although the sampling rate for this study was not sufficient to provide reliable data on the dynamics of the eye movements, our findings are consistent with the reported slower velocities and longer latencies for divergence that have been reported by Hung et

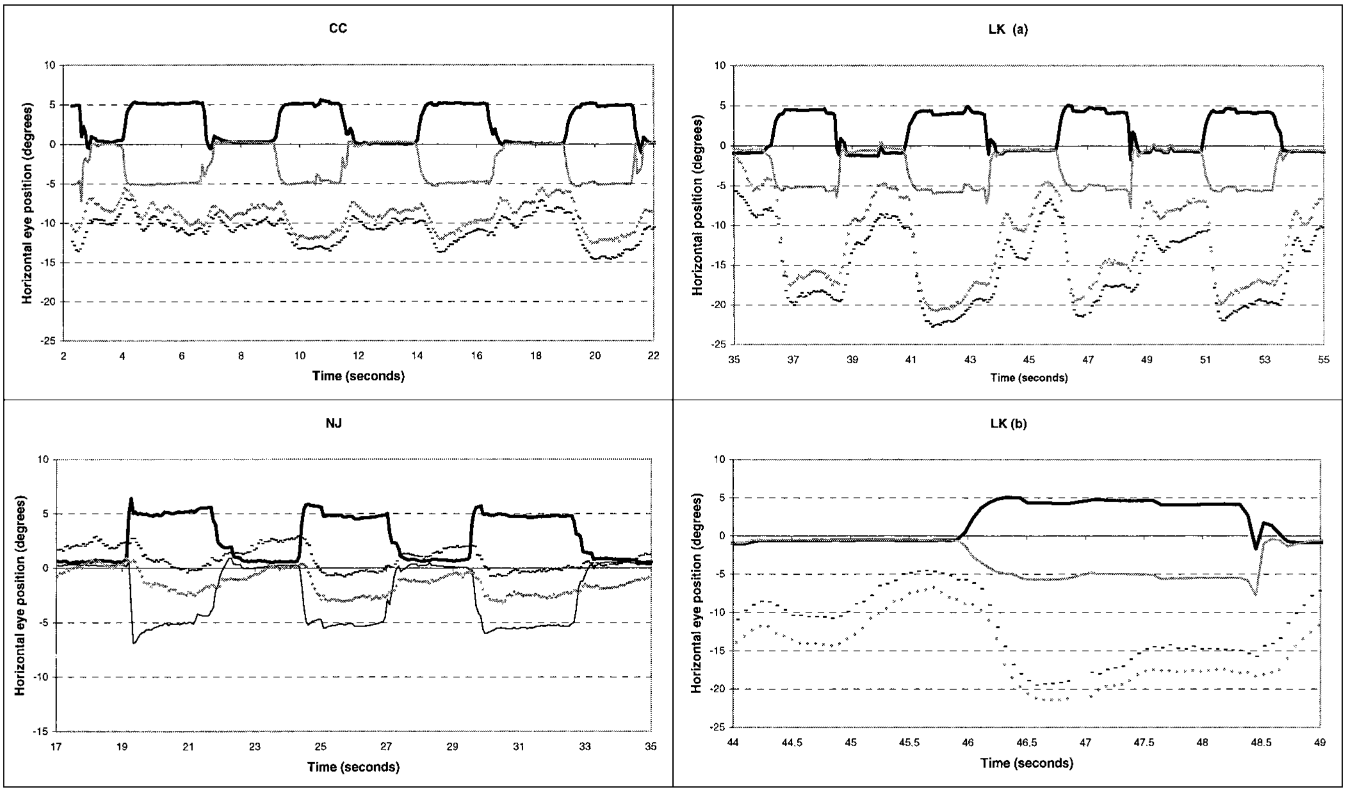

FIGURE 2.

Recordings of eye movements during vergence changes (solid lines) and associated pupillary area (broken lines). Black lines represent the right eye, and gray lines represent the left eye. The Y axis refers to the horizontal position of the eye; pupil measurements are relative only. Recording LK(b) shows the detail of one vergence cycle. For subjects CC and LK, the pupil traces have been displaced downward to assist in interpretation; for subject NJ, they are in their original position to more clearly demonstrate that the change in pupil size is slower than the change in eye position. It can be seen in all cases that eye position is not directly related to pupil size.

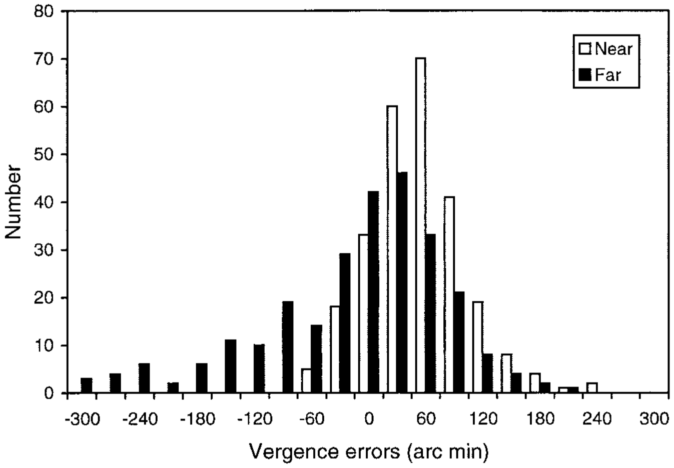

FIGURE 3.

Distribution of mean vergence errors for each vergence change condition for all subjects at both far (black bars) and near (white bars). Most errors are between −120 and +120 min arc for far fixations and between −30 and +120 min arc for near fixations.

al.[24] Studies of the neural pathways for vergence eye movements in experimental animals have identified cells that fire in response to both convergence and divergence movements,[25–29] however the identification of cells in the posterior interposed nucleus of the cerebellum that respond only to divergence and/or relaxation of accommodation[30] indicates that the pathways for convergence and divergence are at least partly independent. Our findings suggest that there are different effects of convergence and divergence on the type and extent of vergence errors during binocular fixation that could be attributed to these neurological factors or possibly to an overall insufficiency of the vergence system. However, they could also be attributed to anatomical factors such as the vasco-elastic properties of the medial and lateral rectus muscles and their associated fascia.

This study has also demonstrated that these misalignments can be affected by the amplitude of vergence change for both distances on binocular fixation errors, with larger changes producing relatively more convergence. The resulting decrease in error size for near fixation with the large and rapid fixation changes may be related to the reduced need for convergence when the eyes are already partly overconverged on the far target. However, this should also result in a change in vergence size with each fixation, an effect that was not evident in this study. The small number of fixations (3–4), although very similar in size within each condition, may have masked this effect.

The absence of diplopia in the presence of significant errors of binocular alignment was a particular finding of this study. However, diplopia in itself is a rare symptom in subjects with normal binocular vision, indicating either that eye movements are always precise or that significant disparity can be tolerated during certain conditions.

TABLE 1.
Data (min arc) for each of the nine conditions of vergence change.

	Far				Near			
	Mean	Median	SD	95% CI[a]	Mean	Median	SD	95% CI
5° Slow (0.25 Hz)	14.01	12.98	35.65	15.99	−49.41	−34.37	69.87	25.43
5° Medium (0.5 Hz)	25.74	12.86	35.32	27.66	−41.38	−36.12	69.23	25.20
5° Fast (1 Hz)	42.10	13.10	36.00	46.87	−30.84	−4.10	79.11	28.79
10° Slow (0.25 Hz)	13.00	19.62	53.91	16.91	−44.28	−14.17	83.53	30.40
10° Medium (0.5 Hz)	20.98	15.45	42.45	20.97	−40.52	−10.78	88.69	32.28
10° Fast (1 Hz)	47.44	17.67	48.55	53.84	−34.99	−6.39	90.92	33.09
15° Slow (0.25 Hz)	36.70	17.84	49.02	32.79	−18.20	+3.23	114.41	41.64
15° Med (0.5 Hz)	58.71	18.29	50.26	41.19	−3.63	+23.54	118.22	43.03
15° Fast (1 Hz)	82.87	22.86	62.81	70.31	−4.05	+34.08	121.40	44.18

[a] 95% CI, 95% confidence interval.

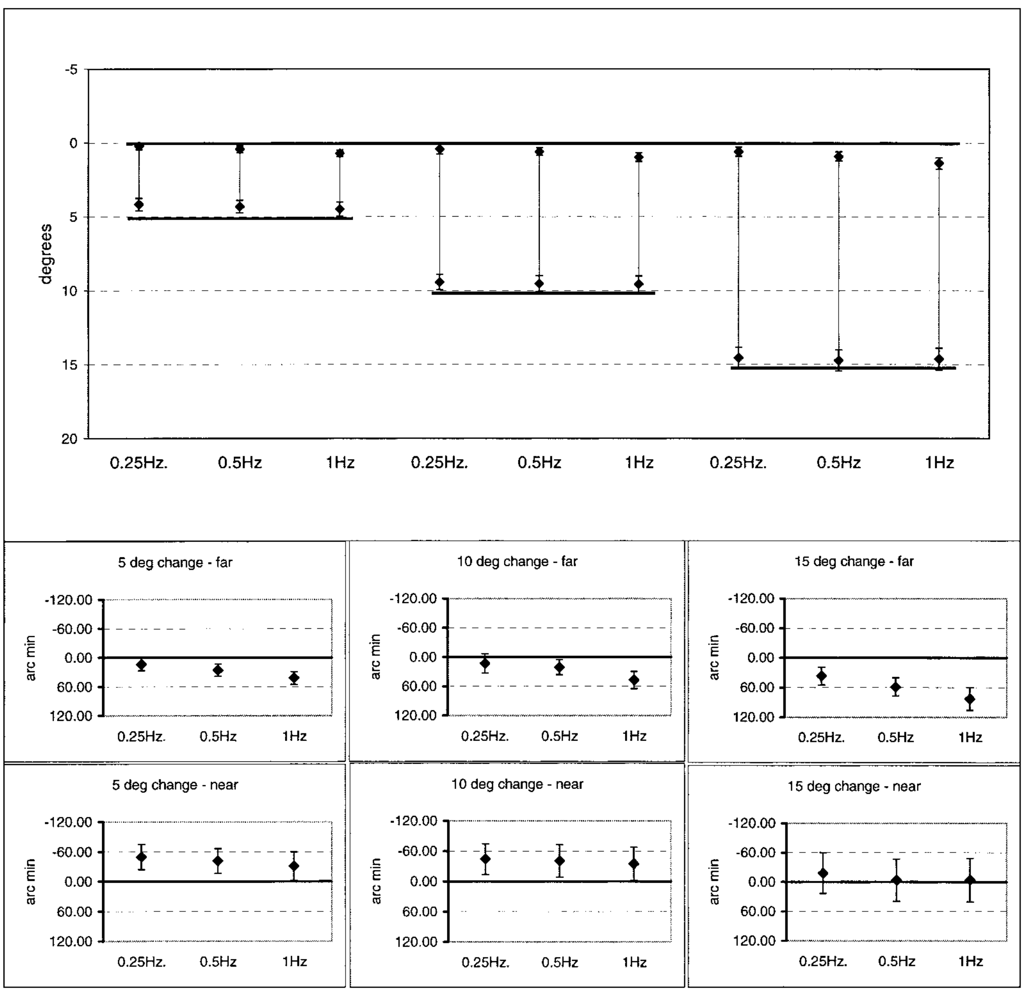

FIGURE 4.

Top figure shows the average range of the vergence movement (in degrees) during all nine conditions. The solid line represents the target position in degrees, and small diamonds represent the recorded vergence position of the eyes. Lower charts show details of the vergence error (in min arc) in each condition. Error bars show 95% confidence intervals. For far fixations, there is a significant effect of both the size of vergence change ($F_{1,28} = 61.8$; $p < 0.001$) and the rate of change ($F_{1,28} = 7.08$; $p = 0.013$) on vergence errors. For near fixations, there is a significant effect ($F_{1,28} = 15.9$; $p < 0.001$) for the angle of change on these errors.

Although the head was stabilized for this experiment, others[11, 17, 31] have demonstrated that images can remain subjectively stable despite significant retinal image disparity induced by head movements. Duwaer[32] demonstrated much smaller disparities using an afterimage technique, however, this is consistent with the differences found between studies using objective and subjective methods. During natural viewing conditions, there is a full visual field with multiple retinal disparities, a person is constantly changing fixation, the person or the person's head may be moving, or other objects in the visual field may be moving. Fixations may be brief and of little importance to the person, so it is unlikely that the alignment of the eyes is always precise. Physiological diplopia in everyday situations is rarely noticed; clinicians are aware that it is often very difficult to demonstrate this phenomenon to someone who was not previously aware of it. The results of this study suggest that it is tolerance of disparity, perhaps associated with frequent eye movements, rather than precision of eye movements that makes diplopia an unusual symptom for most people. As was discussed in the introduction section, studies implying that precise alignment of the eyes is necessary for single vision are normally carried out during experimental conditions or use subjective methods,[1, 4–7, 32] whereas those that have demonstrated tolerance of disparity similar to those of this study are usually carried out during free space conditions that included many of the conditions listed above.[2, 3, 12, 17]

It was evident in many subjects that the large and fast changes of fixation did not allow sufficient time for a stable period of fixation. However, such eye movements do exist in natural conditions, such as many sporting activities, and should be considered part of normal viewing. The characteristics of these movements are similar to those reported by Erkelens et al.,[2] where errors of up to 6° were reported. Other studies[33–36] have shown that suppression of vision can occur during a vergence movement. Although the reported time course of this visual suppression is very short, it may have been influential during the large and fast movements induced in this study. This visual suppression associated with eye movements is a binocular phenomenon, not the uniocular form of suppression that may be expected to accompany a vergence error during fixation. It is possible that any saccadic movements during both the vergence movement and the fixation period could also have contributed to visual suppression, however, the recording system used in this study did not permit a detailed analysis of this possibility.

CONCLUSIONS

Objectively measured errors of symmetrical vergence eye movements of up to 2°, without diplopia, are common in subjects with normal binocular vision. Occasional errors of up to 5° occur. However, even with such large errors, diplopia is not experienced. Vergence errors tend to be those of underconvergence on a near target and overconvergence (or underdivergence) on a far target. These errors are also influenced by rapid, large vergence change, which result in more convergence, thus increasing errors for far fixations and decreasing errors for near fixations. The lack of diplopia, despite relatively large disparities, could be attributed to an extended form of vergence-related suppression, however, it also brings into question the usefulness of Panum's fusional space as an explanatory concept for natural viewing conditions.

ACKNOWLEDGMENT

Received February 13, 2003; revision received May 27, 2003.

REFERENCES

1. Schor C. Fixation of disparity: a steady state error of disparity-induced vergence. Am J Optom Physiol Opt 1980;57:618–31.
2. Erkelens CJ, Steinman RM, Collewijn H. Ocular vergence under natural conditions: II. Gaze shifts between real targets differing in distance and direction. Proc R Soc Lond (B) 1989;236:441–65.
3. Collewijn H, Erkelens CJ, Steinman RM. Voluntary binocular gaze-shifts in the plane of regard: dynamics of version and vergence. Vision Res 1995;35:3335–58.
4. Schor C, Robertson KM, Wesson M. Disparity vergence dynamics and fixation disparity. Am J Optom Physiol Opt 1986;63:611–8.
5. Schor C, Wesson M, Robertson KM. Combined effects of spatial frequency and retinal eccentricity upon fixation disparity. Am J Optom Physiol Opt 1986;63:619–26.
6. Schor CM. The relationship between fusional vergence eye movements and fixation disparity. Vision Res 1979;19:1359–67.
7. Ogle KN, Martens TG, Dyer JA. Oculomotor Imbalance in Binocular Vision and Fixation Disparity. Philadelphia: Lea & Febiger, 1967:xi,372.
8. Hebbard FW. Comparison of fixation disparities obtained by objective and subjective methods. J Opt Soc Am 1962;52:706–12.
9. Kertesz AE, Lee HJ. Comparison of simultaneously obtained objective and subjective measurements of fixation disparity. Am J Optom Physiol Opt 1987;64:734–8.
10. Simonsz HJ, Bour LJ. Covering one eye in fixation-disparity measurement causes slight movement of fellow eye. Doc Ophthalmol 1991;78:141–52.
11. Steinman RM, Collewijn H. Binocular retinal image motion during active head rotation. Vision Res 1980;20:415–29.
12. Erkelens CJ, Van der Steen J, Steinman RM, Collewijn H. Ocular vergence under natural conditions: I. Continuous changes of target distance along the median plane. Proc R Soc Lond B Biol Sci 1989; 236:417–40.
13. Epelboim J. Gaze and retinal-image-stability in two kinds of sequential looking tasks. Vision Res 1998;38:3773–84.
14. Epelboim J, Kowler E, Steinman RM, Collewijn H, Erkelens CJ, Pizlo Z. When push comes to shove: compensation for passive perturbation of the head during natural gaze shifts. J Vestib Res 1995;5: 421–42.
15. Epelboim J, Steinman RM, Kowler E, Pizlo Z, Erkelens CJ, Collewijn H. Gaze-shift dynamics in two kinds of sequential looking tasks. Vision Res 1997;37:2597–607.
16. Epelboim JL, Steinman RM, Kowler E, Edwards M, Pizlo Z, Erkelens CJ, Collewijn H. The function of visual search and memory in sequential looking tasks. Vision Res 1995;35:3401–22.
17. Malinov IV, Epelboim J, Herst AN, Steinman RM. Characteristics of saccades and vergence in two kinds of sequential looking tasks. Vision Res 2000;40:2083–90.
18. Straumann D, Zee DS, Solomon D, Kramer PD. Validity of Listing's law during fixations, saccades, smooth pursuit eye movements, and blinks. Exp Brain Res 1996;112:135–46.
19. Frens MA, van der Geest JN. Scleral search coils influence saccade dynamics. J Neurophysiol 2002;88:692–8.
20. Moore ST, Curthoys IS, McCoy SG. VTM: an image-processing system for measuring ocular torsion. Comput Methods Programs Biomed 1991;35:219–30.
21. Moore ST, Haslwanter T, Curthoys IS, Smith ST. A geometric basis for measurement of three-dimensional eye position using image processing. Vision Res 1996;36:445–59.
22. Yang Y, Thompson K, Burns SA. Pupil location under mesopic, photopic, and pharmacologically dilated conditions. Invest Ophthalmol Vis Sci 2002;43:2508–12.

23. Fogt N, Jones R. Comparison of fixation disparities obtained by objective and subjective methods. Vision Res 1998;38:411–21.
24. Hung GK, Zhu H, Ciuffreda KJ. Convergence and divergence exhibit different response characteristics to symmetric stimuli. Vision Res 1997;37:1197–205.
25. Gnadt JW, Mays LE. Neurons in monkey parietal area LIP are tuned for eye-movement parameters in three-dimensional space. J Neurophysiol 1995;73:280–97.
26. Gamlin PD, Clarke RJ. Single-unit activity in the primate nucleus reticularis tegmenti pontis related to vergence and ocular accommodation. J Neurophysiol 1995;73:2115–9.
27. Gamlin PD, Yoon K. An area for vergence eye movement in primate frontal cortex. Nature 2000;407:1003–7.
28. Mays LE, Gamlin PD. Neuronal circuitry controlling the near response. Curr Opin Neurobiol 1995;5:763–8.
29. Zhang Y, Mays LE, Gamlin PD. Characteristics of near response cells projecting to the oculomotor nucleus. J Neurophysiol 1992;67:944–60.
30. Zhang Y, Gamlin PD, Mays LE. Antidromic identification of midbrain near response cells projecting to the oculomotor nucleus. Exp Brain Res 1991;84:525–8.
31. Steinman RM, Levinson JZ, Collewijn H, van der Steen J. Vision in the presence of known natural retinal image motion. J Opt Soc Am (A) 1985;2:226–33.
32. Duwaer AL. Assessment of retinal image displacement during head movement using an afterimage method. Vision Res 1982;22:1379–88.
33. Manning KA. Eye-movement-dependent loss in vision and its time course during vergence. J Neurosci 1986;6:1976–82.
34. Manning KA, Riggs LA. Vergence eye movements and visual suppression. Vision Res 1984;24:521–6.
35. Hung GK, Sun L, Semmlow JL, Ciuffreda KJ. Suppression of sensitivity to change in target disparity during vergence eye movements. Exp Neurol 1990;110:291–7.
36. Hung GK, Wang TJ, Ciuffreda KJ, Semmlow JL. Suppression of sensitivity to surround displacement during vergence eye movements. Exp Neurol 1989;105:300–5.

Elaine Cornell
Department of Psychology
University of Sydney
New South Wales 2006
Australia
e-mail: e.cornell@fhs.usyd.edu.au