The Relationship between Phoria and the Ratio of Convergence Peak Velocity to Divergence Peak Velocity

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Purpose. The purpose of this study was to investigate the relationship between phoria and the dynamics of vergence eye movements as described by the ratio of convergence average peak velocity to divergence average peak velocity, termed the vergence peak velocity ratio.

Methods. Phoria and vergence step responses were recorded. Three measures of phoria were assessed: baseline phoria, which is the initial phoria measurement; adapted phoria, which is the phoria measured after a visual task; and change in phoria, which is defined as adapted phoria minus baseline phoria. Phoria was modified in two experiments: vergence steps located at different initial positions and different sustained convergent fixations. Four linear regression analyses were conducted to study the interactions among baseline phoria and vergence peak velocity ratio, adapted phoria and vergence peak velocity ratio, baseline and adapted phoria, and baseline phoria and change in phoria.

Results. Baseline and adapted phoria were significantly correlated to vergence peak velocity ratio. Adapted phoria and baseline phoria were also significantly correlated. The change in phoria induced by the vergence steps or a sustained fixation task was independent of the baseline phoria.

Conclusions. These data support that phoria is a factor in the asymmetry between peak velocity of convergence and divergence and that baseline phoria level is not a factor in the amount of change observed in phoria level (adapted phoria minus baseline phoria). Future oculomotor models of vergence should incorporate phoria within the design. (*Invest Ophthalmol Vis Sci.* 2010;51:4017–4027) DOI:10.1167/iovs.09-4560

Vergence is the inward (convergence) or outward (divergence) rotation of the eyes to project the line of sight onto the same point of interest. Disparity is the difference between the image locations in the two eyes with respect to their foveae. Dissociated heterophoria, or simply phoria, is the steady state position of one eye that has no visual stimulus, such as when it is occluded, while the other eye is fixated on a target located along midline. The viewing eye can be fixated on a target typically located at near (40 cm) or at far (6 m). The occluded eye may maintain its position, rotate nasally, or rotate temporally; these three possible positions are termed orthophoria, esophoria, and exophoria, respectively.

When a person binocularly views a visual stimulus at different spatial depths for a prolonged amount of time, a change in phoria is observed that is referred to as phoria adaptation or prism adaptation. Phoria adaptation can be induced by sustained fixation using physical targets, a stereoscope, prisms, or lenses.[1–6] Improvement of phoria adaptation, defined as the ability to change the magnitude of the phoria, has been reported for patients participating in vision therapy to reduce visual symptoms related to prolonged periods of near work.[7] The authors of one study[8] of dark vergence (the resting position of vergence in complete darkness—i.e., phoria in the absence of any visual stimulation) and asthenopic (eye strain) symptoms when working at near—showed that subjects with distant dark vergence exert more convergence and experience stronger asthenopic symptoms than subjects with dark vergence closer to the subject. They conclude that dark vergence should be considered "an indicator for the cause of near-vision asthenopia."[8]

Only a few models have tried to incorporate other factors that may influence the vergence system, such as the tonic or the phoria level.[9–11] Schor's[9] model uses a recruitment mechanism that is an order of magnitude slower than the transient component. As sustained fixation duration is increased, the recruitment of neurons is greater, thereby increasing the output of the sustained component and reducing the drive from the transient component. Hung's[10] model suggests a variable time-constant mechanism in which neurons increase their time-constants proportionally to the sustained fixation duration. In both models, the transient component is considered to be nonadaptable. Furthermore, both models assume identical dynamic behavior during convergence and divergence movements. The only model that could account for near or far adaptation was proposed by Saladin.[11] This model consists of separate sensorimotor pathways for convergence and divergence where each pathway is similar to Schor's[9] model.

Previous studies show that two parameters, fixation disparity and sustained fixation, correlate to the dynamics of disparity vergence. One model successfully predicts fixation disparity using a change in forced convergence with an intraindividual approach.[12,13] This finding has been confirmed using an interindividual experimental design.[14] These studies show that fixation disparity is correlated with the asymmetry between the peak velocity of convergence and divergence. Hence, other parameters, such as phoria and tonic vergence, should be systematically studied to determine whether they are also correlated to the dynamics of the system.

Two studies have investigated how sustained fixation influences the dynamics of disparity vergence.[1,15] Patel et al.[15] studied the response of symmetrical 2°-step changes in disparity after a sustained 6° convergence task of 5, 30, 60, and 90 seconds. Their results showed that the peak velocity of divergence responses decreased significantly after 30 seconds or longer of sustained fixation compared with only 5 seconds,

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Supported in part by a CAREER award from the National Science Foundation (BES-0447713) and from a grant from Essilor, International.

Submitted for publication August 28, 2009; revised October 21, 2009, and January 21 and February 20, 2010; accepted March 1, 2010.

Disclosure: **E.H. Kim**, None; **B. Granger-Donetti**, None; **V.R. Vicci**, None; **T.L. Alvarez**, Essilor (F)

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TABLE 1. Subject Parameters

Subject	Sex	Age	Maddox System Phoria (Δ) Experiment 1	Maddox System Phoria (Δ) Experiment 2	Refraction	AC/A
S1	M	22	2–3 eso	2 eso	Emmetrope	NA
S2	F	21	ortho-1 exo	2 exo	Emmetrope	2:1
S3	M	22	2 exo	2 eso	Emmetrope	2:1
S4	F	29	4 exo	4 exo	Emmetrope	2:1
S5	M	23	6 exo	4 exo	−1.5 D	2:1
S6	M	24	8 exo	6 exo	Emmetrope	2:1
S7	M	23	8 exo	8 exo	Emmetrope	NA
S8	M	29	7 exo	6 exo	Emmetrope	NA
S9	F	29	8 exo	8 exo	−2.0 D	2:1
S10	M	23	10 exo	—	Emmetrope	3:1
S11	M	23	—	8 exo	Emmetrope	3:1

Each subject's sex, age, and baseline phoria were measured using the Maddox rod for the first and second experiments. Refraction and the AC/A ratio are tabulated. Information for the AC/A ratio was not available (NA) for three subjects. Phoria measurement based on the Maddox rod system was used to recruit subjects with a range of phoria levels. eso, esophoria; exo, exophoria; ortho, orthophoria.

whereas the convergence dynamics were unchanged for all the exposure durations. They conclude that the transient component of the horizontal disparity system adapts nonlinearly and independently for convergence and divergence.[15] Ying et al.[1] did not study disparity vergence dynamics but systematically studied the passive decay of divergence from a convergence stimulus of 30° after 4 seconds of fixation and again after 36 seconds of fixation. The dynamics of the divergence decay were faster after 4 seconds of fixation than after 36 seconds of fixation, suggesting that sustained fixation influences divergence decay dynamics.[1]

The main objective of this study was to investigate the relationship between phoria and vergence dynamics, as described by the ratio of convergence average peak velocity to divergence average peak velocity. Three forms of phoria were assessed: baseline or initial phoria, adapted phoria (phoria measured after a visual task), and change in phoria (adapted phoria minus baseline phoria). Once this relationship is understood, more studies can be conducted to facilitate our understanding of why near work induces asthenopic symptoms in some persons. For example, patients with vergence dysfunction can have a reduced ability to change their phoria level compared with healthy controls. Hence, the ability to adjust phoria level rather than baseline phoria may be a better indication of asthenopic symptoms.

SUBJECTS, MATERIALS, AND METHODS

Subjects

Twelve subjects, 18 to 29 years of age, who could easily perform the experiment described here participated in this study. Eight of the subjects were men, and four were women. One subject was esophoric, two subjects were orthophoric, and nine subjects were exophoric in their initial baseline phoria recording assessed with the Maddox rod and the limbus eye movement tracking system. All subjects had normal binocular vision assessed by the Randot Stereopsis and near point of convergence tests. Ten subjects were emmetropes. Two subjects were myopes (average prescription was −1.75 D). These subjects wore their corrective refraction during the experiments. The research was conducted in accordance with the tenets of the Declaration of Helsinki. All subjects signed informed consent forms before the experiments, which were approved by the New Jersey Institute of Technology Institutional Review Board. None of the subjects knew the objective of this study before the experiment. Subjects S1 through S10 participated in the first experiment, which used vergence steps to evoke phoria adaptation. Subjects S1 through S9 and S11 participated in a second experiment, which used a 5-minute sustained fixation task to evoke phoria adaptation. Subject parameters are summarized in Table 1. Subjects S3, S5, and S12 participated in a validation test to determine how monocular versus binocular calibration influenced the peak velocity of vergence-step responses.

Materials and Apparatus

Eye movements were recorded using an infrared ($\lambda = 950$ nm) system manufactured by Skalar Iris (model 6500; Delft, The Netherlands). All eye movements were within the linear range of the system (±25°). Visual stimuli were displayed using a haploscope. Two computer screens were used to generate a symmetrical disparity vergence stimulus along the subject's midline. The stimulus was a green vertical line 2 cm in height and 2 mm in width with a black background. Two partially reflecting mirrors projected the two vertical lines from the computer screens into the eyesight of the subject. Before the experiment, stimuli from the computer screens were adjusted with mirrors to calibrate the visual stimulus with real targets located at measured distances from the subject's midline. During the experiment, only the visual stimulus displayed on the computer screen was seen by the subject. The subject's head was restrained using a custom chin rest to eliminate head movement, thus avoiding any vestibular influences in the experiment.

The stimuli screens were placed 40 cm away from the subject; hence, the accommodative stimulus was held constant. A previous study showed that accommodative vergence does not influence disparity vergence dynamics because accommodative vergence begins approximately 100 to 200 ms after the latency seen in the disparity-driven component.[16] Any changes in the eye movement peak velocity ratio were assumed to be attributed to the disparity vergence system.

Left eye and right eye responses were recorded, calibrated, and saved separately for offline analysis. Digitization of eye movements was performed with a 12-bit digital acquisition hardware card using a range of ±5 V (6024 E series; National Instruments, Austin, TX). The entire system was controlled by a custom program (LabVIEW 8.0; National Instruments) that generated the visual stimulus and digitized the individual vergence eye movements sampling at a rate of 200 Hz. The minimum sampling rate for vergence has not been published. However, saccadic eye movements contain most of their information within the first 35 Hz when analyzing saccades with a magnitude of 5° to 20°. Hence, saccadic eye movements should be sampled at a minimum rate of 70 Hz.[17] Given that the saccadic system contains higher frequencies than the vergence system, a sampling rate of 200 Hz was sufficient to digitize vergence eye movements to avoid aliasing.

Calibration

Three calibration methods were used in this study—two types (binocular and monocular) for vergence step responses and a third type for phoria measures.

Binocular Calibration for Vergence Step Responses. Calibration for vergence step responses was composed of two points that were the initial and final position of the step stimuli. The two-point calibration was viewed binocularly and was the initial and final combined vergence demand of the step stimuli.

Monocular Calibration for Vergence Step Responses. The final amplitude of disparity vergence, which cannot be detected with binocular calibration applied to the step responses, has been shown to vary potentially from accommodation and fixation disparity.[18] Hence, the following supplemental control experiment was conducted to investigate the influence of binocular versus monocular calibration on the peak velocity of vergence step responses. Before a series of step responses, a monocular stimulus was presented to the left eye at the initial and final position of the left eye stimulus. This was repeated for the right eye, when the subject was also presented with the initial and final position monocularly.

Calibration for Phoria Measurements. A four-point calibration was used for phoria measurements to ensure that eye movement responses were within the calibration range. This calibration protocol was chosen because the amount of change in the phoria level induced by the sustained fixation task or from a series of vergence steps located at different initial positions was unknown before the study. The four calibration points were observed monocularly with the right eye. The first calibration stimulus was 4° into the left visual field from midline. The second calibration stimulus was on midline. The third and fourth points were 4° and 9° into the right visual field. These calibration points equate to a potential phoria range of 7Δ esophoria to −15.8Δ exophoria (1 prism diopter = 100 tan(θ)). Theta is the phoria angle in degrees.

Phoria Measurement

The dissociated near phoria (phoria measured from 40 cm/16 in) was subjectively measured using a Maddox rod with the Bernell muscle imbalance measure (MIM) card (Bernell Corp., South Bend, IN), which has a resolution of 1Δ and a range of 28Δ exophoria to 28Δ esophoria. The MIM card is calibrated for the right eye; hence, the phoria was measured with the left eye fixating on a target. The target was placed 40 cm or 16 inches away from the subject's midline, which equates to an accommodative demand of 2.5 D.

Dissociated near phoria was measured quantitatively during the present experiment using an infrared (λ = 950 nm) limbus tracking system (model 6500; Skalar Iris). The experiment was conducted in a dark room. The subjects binocularly viewed a pair of vertical lines that stimulated 4.22° rotation in each eye and corresponded to a target 40 cm away from the subject's midline, equating to a 2.5D accommodative demand. This is the same distance at which clinicians measure near-dissociated phoria. A binocular target was presented for 2.5 seconds, and the right eye stimulus was extinguished so that the right eye would decay to the steady state phoria level. Decay to phoria was recorded for 15 seconds. The right eye movement decaying to the phoria level signal was converted to prism diopters (the standard unit used clinically). The right eye decay to phoria was always measured from the initial position of 4.22°, with an accommodative demand of 2.5 D for all analyses in this study. Before this study, phoria measurements using our eye movement monitor system were validated with the Maddox rod using the MIM card (Bernell Corp.) and the alternate cover test to assess precision and accuracy of the near-dissociated phoria.[19]

Our previous research studied 15 subjects who were not included in this present study.[19] The investigation compared each subject's baseline phoria measurement with the phoria measurement after 5 minutes of sustained fixation on a physical target located at far (172 cm away from midline) and near (21 cm away from midline) using a limbus tracking system and the Maddox rod. These physical targets corresponded to a 2° combined vergence demand and a 16° vergence demand assuming an interpupillary distance of 6 cm. Correlation results were high when comparing the limbus tracking system to the Maddox rod for baseline phoria measurements (R^2 = 0.72; P = 0.008), after far adaptation (R^2 = 0.73; P = 0.007), and after near adaptation (R^2 = 0.66; P = 0.01). The linear fit equation calculated by using a least-squared errors technique showed that the phoria measured using the limbus tracking system was 0.99, 1.04, and 0.98 times the phoria measured from the Maddox rod during the baseline, far adaptation, and near adaptation experiments, respectively. The Maddox phoria measurements were 1.47Δ, 0.56Δ, and 1.44Δ more esophoric from baseline, far adaptation, and near adaptation recordings, respectively, based on the linear regression analysis. This study concluded there is an approximately a one-to-one relationship between the two systems, in which the flashed Maddox rod measurements are more esophoric than the limbus tracking system measurements. Precision testing showed that the SD of repeated phoria measurements was between 0.7Δ and 1.1Δ for the limbus tracking system compared with 0.8Δ to 4Δ from other phoria studies reporting repeatability from the literature.[20,21]

Experimental Protocol to Study the Relationship between Baseline Phoria, Phoria Measured after a Series of Vergence Steps, Change in Phoria, and Vergence Peak Velocity Ratio

The experimental design for the first experiment is shown schematically in Figure 1A. Subjects were dark adapted for 5 minutes, and the initial phoria level was measured as the baseline or preadapted phoria. Five minutes of dark adaptation allowed for the uncoupling of accommodation and vergence to relax both systems.[22] Phoria was again measured after the vergence step stimuli to determine whether phoria adaptation occurred given that the vergence step stimuli had different initial positions; this visual task lasted between 2 and 3 minutes, which could provoke phoria adaptation.

Depending on the subject, 20 to 30 convergence and divergence responses for three different ranges were recorded and were randomly intermixed to decrease prediction. Convergence and divergence steps used a 4° step change in disparity vergence. The vergence steps had initial positions that occurred at different ranges classified as three types: near, middle, and far. The initial position of the near convergent step stimulus was 12.44°, whereas the initial position of the near divergent step stimuli was 16.44°. The initial position of middle and far convergent step stimuli were 8.44° and 4.44°, respectively, whereas the initial position of the middle and far divergent step stimuli were 12.44° and 8.44°, respectively. The experiment was designed around the combined symmetrical vergence initial position of 8.44°, which corresponds to 40 cm away assuming an interpupillary distance of 6 cm. Then 4° increments were chosen closer or farther from the subject to establish the range of experimental stimuli. Near-dissociated phoria is measured clinically at 40 cm; hence, the experimental design used this initial position. These vergence steps were used to quantify the vergence peak velocity ratio, defined as convergence average peak velocity divided by divergence average peak velocity. Furthermore, since the steps were observed at different initial positions (range, 16.44°-4.44°), the series of vergence steps may also adapt the phoria.

The step stimuli presentation were randomized, intermixed, and delayed between 0.5 second to 2.0 seconds to ensure that prediction and voluntary vergence did not influence the results.[23–25] Each vergence step stimulus was recorded for a duration of 3 seconds. There were 20 to 30 convergence and 20 to 30 divergence responses collected at each range. Subjects viewed between 2 and 3 minutes of vergence stimuli, and then a phoria measurement was recorded. The 2 to 3 minutes of eye movements is hypothesized to adjust the phoria level. To summarize the first experimental design, baseline phoria was measured, followed by vergence steps in the middle range; phoria was measured again to determine whether the middle steps adapted the phoria. This was repeated for near steps, followed by phoria measure-

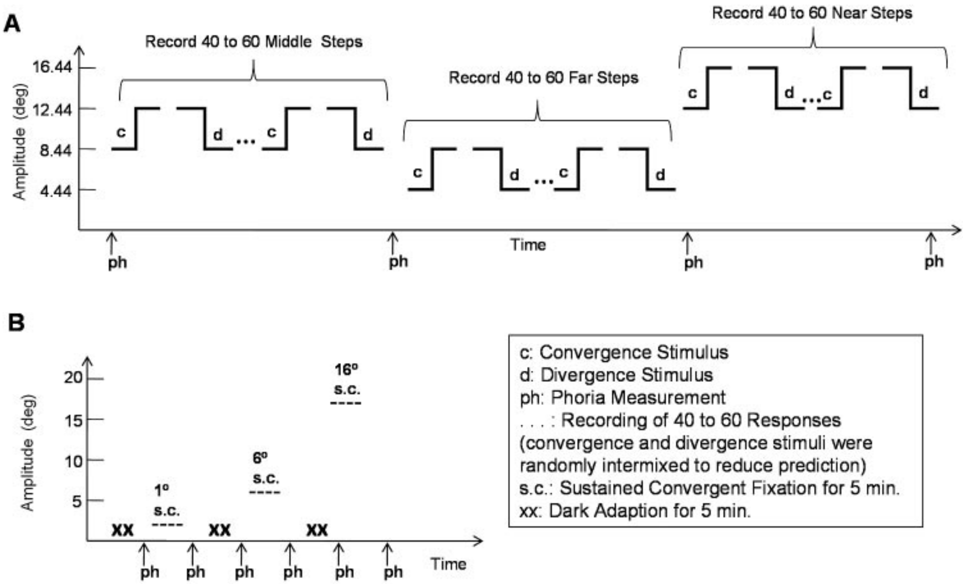

FIGURE 1. (**A**) Experimental design of the study investigating the relationship between baseline phoria, adapted phoria after a series of vergence steps, change in phoria, and vergence peak velocity ratio. (**B**) Experimental design of the study investing baseline phoria and adapted phoria after 5 minutes of a sustained convergent fixation task.

ment. Last, far steps were recorded followed by a phoria measurement. This experiment was designed to study the relationship between baseline phoria; adapted phoria, which is the phoria measured after vergence steps; change in phoria, which is the adapted phoria minus the baseline phoria; and the vergence peak velocity ratio.

Experimental Protocol of Baseline Phoria and Phoria Adaptation Using a Sustained Fixation Task

To investigate the relationship between baseline phoria and adapted phoria, two types of phoria adaptation were evoked. The first experiment using the vergence steps located at three different ranges measured phoria before and after vergence steps. However, to further investigate the relationship between baseline phoria and adapted phoria, a secondary experiment was conducted that used a 5-minute sustained fixation task. Other studies have shown that beyond 5 minutes of prism adaptation, relatively negligible changes in phoria occur.[26]

Ten subjects who had a range of baseline phoria levels (some were esophores, orthophores, or large exophores) participated in a phoria adaptation experiment using a sustained convergent visual target located at three positions, shown schematically in Figure 1B. Phoria was initially measured after the subject was dark adapted for 5 minutes. The subject fixated on a 1° sustained convergent target for 5 minutes, and then phoria was measured. The subject was placed in the dark for 5 minutes to allow the phoria level to deadapt or return to the baseline phoria level from the previous visual task to minimize the effects of residual phoria adaptation. Baseline phoria was again measured to ensure that it was similar to the initial baseline phoria level. The subject was asked to fixate on a 6° sustained convergent target, and phoria was measured again. Afterward, the subject was placed in the dark for 5 minutes to allow the phoria level to deadapt, and phoria was measured to ensure it returned to approximately the baseline. Then the subject fixated on a 16° target for 5 minutes, followed by a phoria measurement. This experiment was designed to study baseline phoria and its relationship to adapted phoria. Furthermore, this experiment investigated whether the baseline phoria was correlated to the change in phoria level (the difference between adapted phoria and baseline phoria).

Instructions to Subjects

All subjects participated in one habituation session to minimize the influence of motor learning. Subjects initiated all experimental trials using a trigger button and were asked to not blink until they heard an auditory tone. The habituation session allowed subjects to learn when to press the trigger button to initiate an experiment and when to blink between experimental trials. For the step responses, subjects were asked to fuse the binocular stimulus. For phoria measurements, subjects were asked to relax and view the stimulus presented to the left eye while the right eye decayed to its resting position. Data from the habituation session were not analyzed.

Data Analysis on Vergence Eye Movement Responses

A custom math program (MATLAB, version 7.0; MathWorks, Waltham, MA) was used for all data analysis. Left eye and right eye movement data were converted to degrees using individual calibration data as discussed. The system has a high degree of linearity, within 3% between $\pm 25°$ horizontally.[27] Vergence was calculated by subtracting the right eye movement from the left eye movement to yield a net vergence response. Blinks and saccadic eye movements were easily identified because of their faster dynamics compared with vergence. Responses with blinks at any point during the movement or with saccades during the transient vergence movement were omitted from the analysis because saccades are known to increase the velocities of vergence responses.[28] To ensure saccades were not present during the transient part of the response, the left eye and the right eye vergence position and velocity responses were individually inspected. Saccades were easily identified, especially within the left eye or right eye velocity trace, because of their faster dynamics compared with vergence. Furthermore, the version signal was calculated by summating the left eye movement and the right eye movement together and then dividing by two to determine whether saccades were present during the transient portion of the movement. Convergence responses were plotted as positive, and divergence responses were plotted as negative.

Vergence peak velocity was assessed using a two-point central difference algorithm to compute the vergence velocity response.[29] The two-point central difference algorithm inherently filters the data. To ensure that the range used within the algorithm did not influence the peak velocity, only five data points were used in each velocity point calculation. The number of data points was adjusted between three and seven, and peak velocity did not change. Hence, a range of five data points does not introduce artifacts to the peak velocity calculation. Data were not further filtered using a bandpass

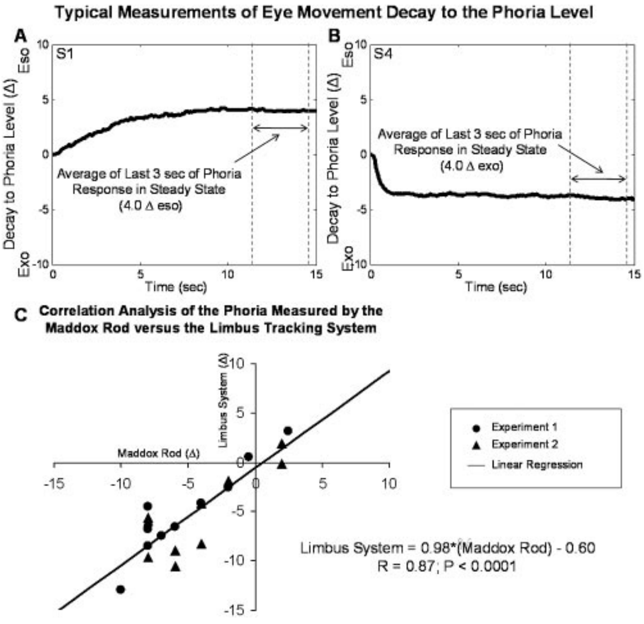

FIGURE 2. Examples of esophoric (**A**) and exophoric (**B**) responses recorded from a limbus eye movement monitor. Phoria is calculated as the average of the last 3 seconds of the recording shown in both figures. Esophoria is plotted as positive and exophoria is plotted as negative. (**C**) Comparison of the limbus tracking system used to measure phoria and the Maddox rod, which is an established clinical standard.

filter or other filtering techniques. The maximum value of the velocity trajectory, peak velocity, was used to calculate the vergence peak velocity ratio.

On inspection of the peak velocity measures of convergence and divergence, responses from the subjects revealed that some were faster or slower in responding than others. Hence, to normalize the data such that the dynamics of the subjects could be compared, the vergence peak velocity ratio was calculated. Vergence peak velocity ratio in this article is defined as convergence average peak velocity divided by divergence average peak velocity. The vergence ratio exhibited how fast or how slow convergence was with respect to divergence for a subject. Some subjects had faster or slower convergence and divergence peak velocities than other subjects. Briefly, this index can be summarized as follows:

Vergence Ratio >1: Convergence Average Peak Velocity $>$ Divergence Average Peak Velocity

Vergence Ratio <1: Convergence Average Peak Velocity $<$ Divergence Average Peak Velocity

Vergence Ratio $= 1$: Convergence Average Peak Velocity $=$ Divergence Average Peak Velocity

Data Analysis on Phoria Responses

The eye movement response decaying to phoria was calibrated and converted to the units of prism diopters (Δ). The steady state phoria level was calculated by averaging the last 3 seconds of the response. The last 3 seconds were used because all movements reached their steady state before 12 seconds of the decay to phoria, which was observed empirically. Examples of eye movement responses decaying to the phoria position are shown in Figure 2. Esophoria was plotted as positive as shown in Figure 2A, and exophoria was plotted as negative as shown in Figure 2B. Maddox rod recordings were used to recruit a population of subjects with a range of phoria levels and to provide a clinical correlation to our limbus tracking system. Our limbus tracking system is highly correlated to the Maddox rod, as shown in Figure 2C. Linear regression shows that the baseline phoria measured from the limbus system $= 0.98 \times$ Maddox rod $- 0.60\Delta$, with a correlation of $R = 0.87$ ($P < 0.0001$). Phoria measurements from the Maddox rod were not used in other analyses. For the rest of the analyses, phoria measurements from the limbus tracking system were used to assess correlation between the parameters.

Statistical Analysis

Linear regression analyses were used to assess the correlation between baseline phoria and vergence peak velocity ratio, adapted phoria and vergence peak velocity ratio, baseline phoria and adapted phoria, and baseline phoria and change in phoria (adapted phoria $-$ baseline phoria). The analysis was calculated using technical computing software (MATLAB, version 7.0; MathWorks). Baseline phoria versus adapted phoria and baseline phoria versus change in phoria were studied when adaptation was first induced with vergence steps and again when it was induced with 5 minutes of a sustained convergent task.

Repeated-measures of ANOVA was used to determine whether baseline phoria was significantly adapted after a series of vergence steps located at different initial positions and three sustained convergent tasks located at different spatial depths. Statistics were calculated using NSC2004 (Number Cruncher Statistical System, Kaysville, UT) software, and figures were generated using the technical computing software (MATLAB, version 7.0; MathWorks).

RESULTS

Comparison of Binocular and Monocular Calibration for Vergence Step Responses

The original design of the experiment used two-point binocular calibration for the vergence step responses. Validation was conducted to determine whether a binocular calibration protocol yielded significantly different vergence peak velocity results compared with a monocular calibration protocol. Results are reported in Table 2. Responses were reconstructed using monocular and binocular calibration. Peak velocity was measured from convergence and divergence responses located at the near and far ends of the experimental design range. Peak velocities with the corresponding vergence peak velocity ratio (convergence peak velocity/divergence peak velocity) were compared. There was a 0.47% to 1.72% difference in peak velocity when comparing convergence and divergence steps constructed using two different calibration methods recorded at the near and far ranges used in this study. For the vergence ratio parameter, there was a 0.04% to 2.02% difference when velocity was calculated using the two calibration methods. Using a paired *t*-test to compare convergence and divergence peak velocities recorded at near and far, data were not significantly different ($P = 0.5$). Hence, either type of calibration (monocular or binocular) would yield similar results. Step responses presented in the Results section used a binocular calibration procedure to calculate the peak velocity for convergence and divergence responses.

Comparison of Baseline Phoria, Adapted Phoria Measured after a Series of Vergence Steps, Change in Phoria, and Vergence Peak Velocity Ratio

Figure 3 shows the average 4° convergence and divergence, positions, and velocity responses of the middle step stimuli of three subjects. Subject S1, a small esophore, had faster average convergence peak velocity than the average divergence peak velocity. Subject S3, a small exophore, exhibited a similar average convergence and divergence peak velocity. Conversely, subject S9, a large exophore, produced a faster average

TABLE 2. Calibration Comparison

	Subject											
	S3				S5				S12			
	Bino	Mono	Diff (%)	*n*	Bino	Mono	Diff (%)	*n*	Bino	Mono	Diff (%)	*n*
Near Responses (between 16.44° and 12.44° combined vergence demand)												
Convergence peak velocity	20.6 ± 2.3	20.8 ± 3.7	0.97	17	17.6 ± 4	17.8 ± 4.9	1.14	10	17.2 ± 4.4	17.3 ± 4.4	0.58	20
Divergence peak velocity	19.4 ± 5.0	19.2 ± 4.2	1.03	15	27.5 ± 4.5	27.3 ± 5.6	0.73	10	12.7 ± 3.1	12.6 ± 2.4	0.79	15
Vergence peak velocity ratio	1.062	1.083	2.02		0.640	0.652	1.88		1.354	1.373	1.38	
Far Responses (between 8.44° and 4.44° combined vergence demand)												
Convergence peak velocity	21.3 ± 2.4	21.2 ± 2.6	0.47	16	23.8 ± 3.3	23.4 ± 2.6	1.68	15	20.9 ± 3.1	21.1 ± 3.6	0.96	20
Divergence peak velocity	13.2 ± 3.3	13.1 ± 2.2	0.76	11	11.6 ± 2.1	11.4 ± 1.7	1.74	15	12.6 ± 2.6	12.7 ± 3.2	0.79	13
Vergence peak velocity ratio	1.614	1.618	0.29		2.052	2.053	0.04		1.659	1.662	0.16	

Comparison of mean convergence and divergence peak velocity (°/s ± SD) with vergence peak velocity ratio (convergence peak velocity divided by divergence peak velocity) using a binocular calibration (Bino) and a monocular calibration (Mono). The difference (Diff) between the methods is shown as the absolute difference between binocular minus monocular divided by binocular data divided by 100. *n,* number of samples analyzed.

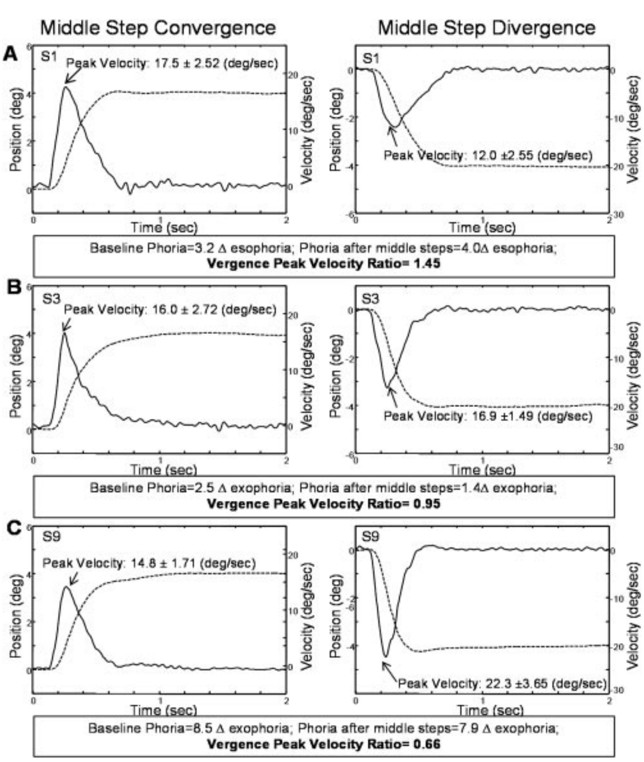

FIGURE 3. Average 4° convergence (*left*) and divergence (*right*) step position responses (*dashed line*) and velocity trace (*solid line*) from middle vergence step stimuli for 3 of 10 subjects (**A**, S1; **B**, S3; **C**, S9). Convergence (plotted from 0° to 4°, or a 4° disparity change) is plotted as positive, and divergence (plotted from 4° to 0°, or a 4° disparity change) is plotted as negative.

divergence peak velocity compared with convergence peak velocity.

An initial analysis compared convergence peak velocity with phoria and divergence peak velocity with phoria. Convergence peak velocities were weakly correlated with the baseline phoria, where the correlation coefficients were $r = 0.50$, $r = 0.40$, and $r = 0.17$ for the middle, far, and near step experiments, respectively. Similarly, the correlation coefficients for the comparison of convergence peak velocities and the phoria measured after the vergence steps (adapted phoria) were not statistically significant ($r = 0.35$, $r = 0.44$, and $r = 0.28$ for the middle, far, and near step experiments, respectively.) Divergence peak velocities were correlated more closely with phoria than were convergence peak velocities. Correlation coefficients for the comparison of divergence peak velocities and baseline phoria were $r = 0.68$, $r = 0.74$, and $r = 0.78$ for middle, far, and near step experiments, respectively. For comparison with the adapted phoria, the correlations were $r = 0.74$, $r = 0.67$, and $r = 0.70$ for middle, far, and near steps experiments, respectively. However, the ratio of convergence peak velocity to divergence peak velocity resulted in stronger correlations. The ratio takes into account that some subjects were innately faster or slower than others and represents the balance between these two systems. The vergence ratio was important because differences in peak velocities may mask the correlation between phoria and convergence peak velocity or phoria and divergence peak velocity. All average convergence and divergence peak velocities from the different types of responses with the three initial positions—far, middle, and near—are shown in Figure 4.

Phoria levels of subjects S1 through S10 ranged from the largest esophore (subject S1) to the largest exophore (subject S10). Notice that vergence ratios were greater for subjects who were esophores, whereas vergence ratios were lower for subjects who were larger exophores. Corresponding limbus tracking phoria results from all subjects were shown in Figure 5. Data were statistically analyzed using repeated-measures ANOVA. The main factor analyzed was the adapting vergence

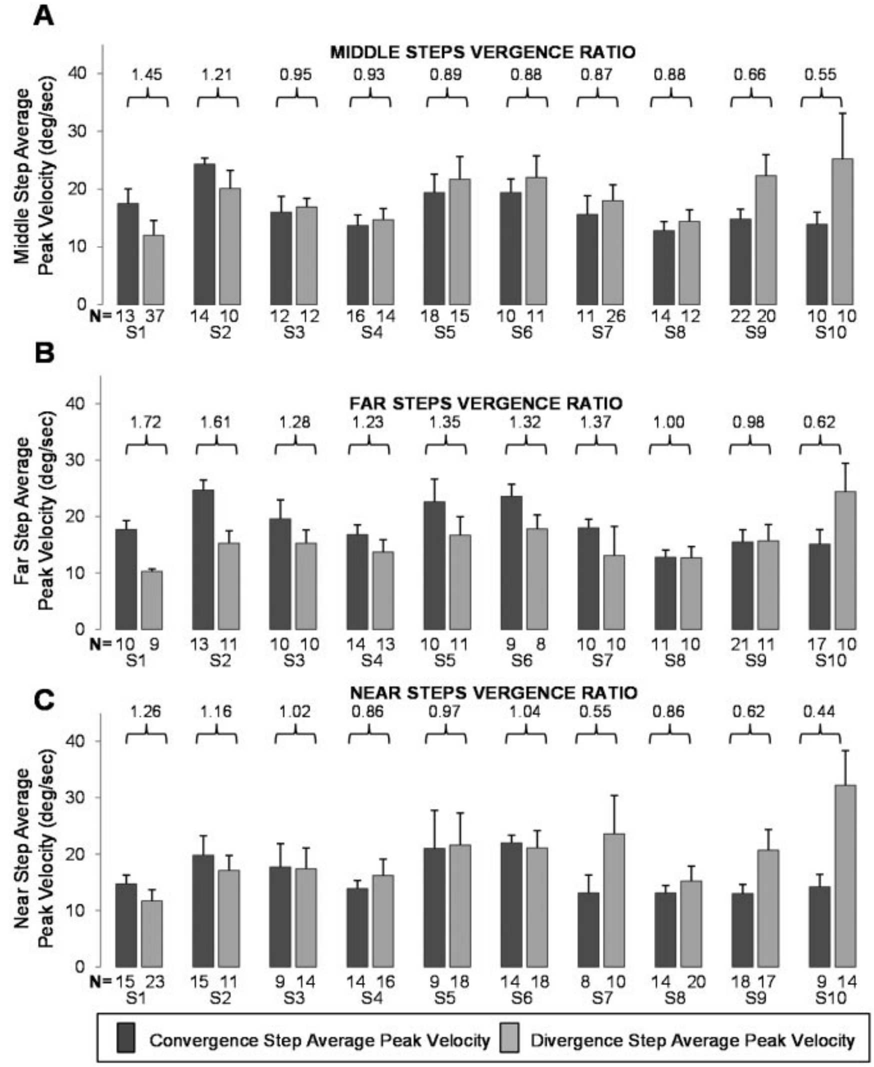

FIGURE 4. Mean peak velocity (°/s) of 4° convergence and divergence responses from three different initial positions (**A**–**C**), with the SD and number of samples analyzed during experiment 1. Data were plotted from the subject who was most esophoric (S1) to the subject who was most exophoric (S10). All limbus tracking phoria measures are plotted in Figure 5.

position (baseline, after far steps, after middle steps, and after near steps). After approximately 40 to 60 vergence steps measured from different initial conditions, the phoria was significantly modified [$F(3,27) = 28.65$; $P < 0.001$]. Post hoc analysis using a Bonferroni all pairwise test indicated that the baseline phoria measurement was significantly different from the phoria measured after the vergence steps with a near initial position. When comparing the baseline phoria with the adapted phoria measures after vergence steps, the phoria became significantly more esophoric after the near vergence steps were collected (initial positions: 12.44° for convergence, 16.44° for divergence). The phoria became more exophoric compared with

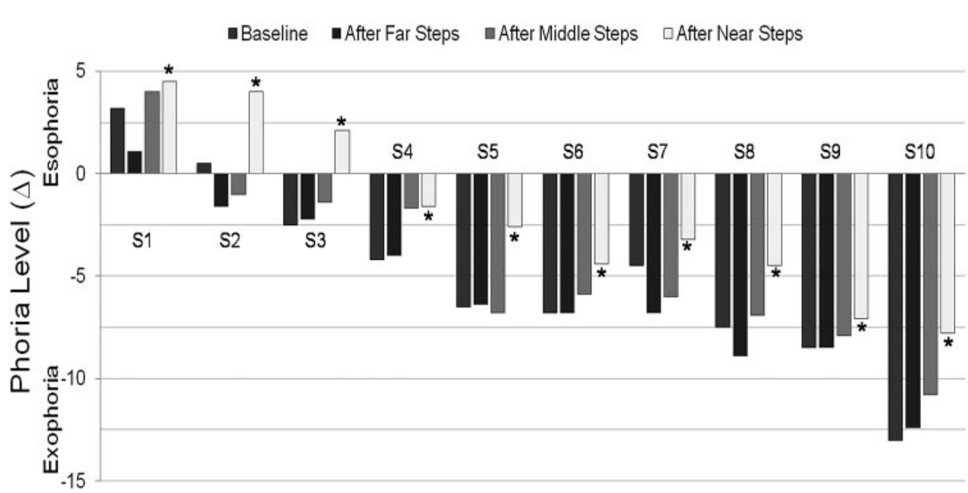

FIGURE 5. Near-dissociated phoria measurements (Δ) using the limbus tracking system during the experimental session. Bonferroni all pairwise multiple comparison test showed that the baseline phoria was significantly different from the phoria measurement after 40 to 60 near vergence steps (initial positions: 16.44° for divergence, 12.44° for convergence) were recorded (*asterisks*).

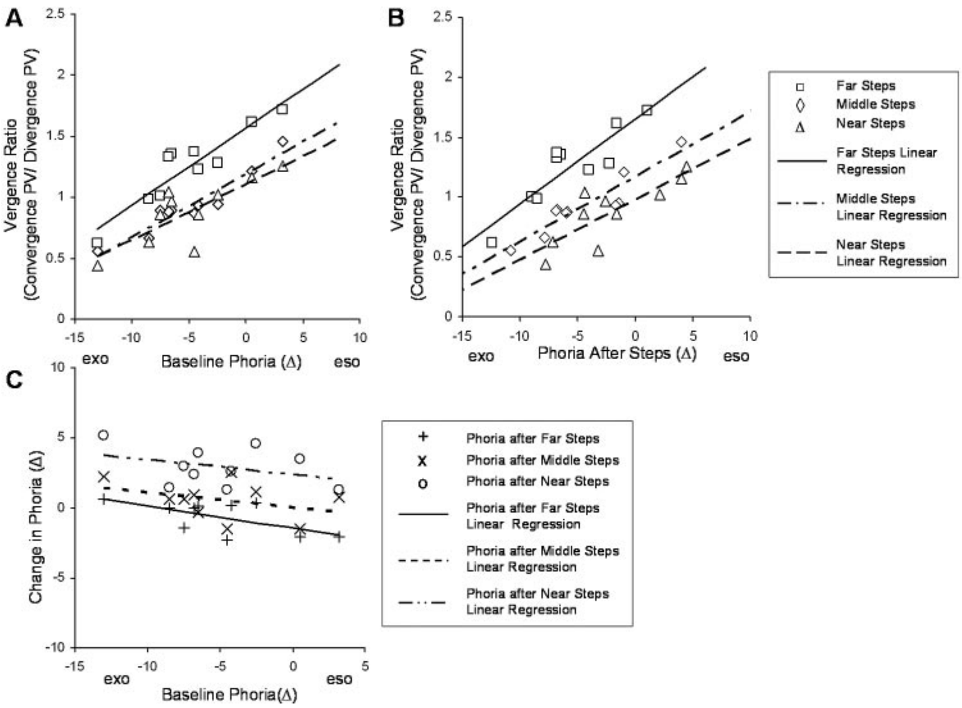

Figure 6. (**A**) Correlation of baseline phoria with vergence ratio (convergence peak velocity [PV] divided by divergence PV) showing a high correlation for far, middle, and near steps. Curve fit equations are as follows: ratio = 0.064 × baseline phoria + 1.57 (far steps); ratio = 0.052 × baseline phoria + 1.19 (middle steps); and ratio = 0.046 × baseline phoria + 1.11 (near steps). (**B**) Correlation of adapted phoria after each step session (far, middle, or near) compared with its corresponding vergence peak velocity ratio (e.g., middle step vergence peak velocity ratio versus phoria measurement after middle steps). Phoria measured after a series of vergence steps was also highly correlated to the vergence peak velocity ratio. Curve fit equations are as follows: vergence ratio = 0.071 × adapted phoria + 1.65 (far steps); ratio = 0.054 × adapted phoria + 1.17 (middle steps); and ratio = 0.050 × adapted phoria + 0.98 (near steps). (**C**) Baseline phoria was not correlated to the change in phoria (adapted phoria minus baseline phoria) after a series of far, middle, and near vergence steps.

baseline measures after the far steps were recorded (initial positions: 4.44° for convergence, 8.44° for divergence). A secondary experiment was conducted using a larger range of viewing distances with a 5-minute sustained convergence task intended to evoke a greater amount of phoria adaptation.

A subject's vergence peak velocity ratio was correlated to the baseline phoria for middle ($r = 0.95$; $P < 0.0001$), far ($r = 0.92$; $P < 0.0001$), and near ($r = 0.80$; $P = 0.01$) steps, as shown in Figure 6A. Curve fit equations revealed that the regression lines were approximately parallel. This behavior was also observed when studying a person's adapted phoria measured after vergence steps. The adapted phoria level measured after steps was correlated to the vergence peak velocity ratio of the middle ($r = 0.94$; $P < 0.0001$), far ($r = 0.89$; $P < 0.0001$), and near ($r = 0.83$; $P = 0.005$) steps shown in Figure 6B. Curve fit equations also showed that the linear fits were approximately parallel. The baseline phoria was also correlated with the adapted phoria measured after vergence steps located at middle ($r = 0.95$; $P < 0.0001$), far ($r = 0.92$; $P < 0.001$), and near ($r = 0.91$; $P < 0.0001$). Three other dynamic measures were correlated with the baseline and adapted phoria. They were the difference between convergence peak velocity and divergence peak velocity, the difference between convergence and divergence peak velocity divided by the summation of convergence and divergence peak velocity, and the square root of the ratio of convergence to divergence peak velocity. None of these parameters showed stronger correlation with baseline or adapted phoria compared with the vergence peak velocity ratio.

However, the baseline phoria was not correlated to the change in phoria (adapted phoria − baseline phoria) when the adapted phoria was measured after middle ($r = 0.62$; $P = 0.05$), far ($r = 0.36$; $P = 0.30$) or near ($r = 0.36$; $P = 0.31$) steps shown in Figure 6C. It was unclear whether this independence could be attributed to the form of adaptation. For example, if the phoria was more strongly adapted with the use of a 5-minute sustained convergent task rather than a series of vergence steps, a correlation could have been present. Therefore, a secondary experiment using a 5-minute sustained convergent task was conducted.

Baseline Phoria Relation to Phoria Adaptation Induced Using 5 Minutes of Sustained Fixation

Figure 7 shows the results of the phoria measures in 10 subjects for baseline and adapted phoria measured after 5 minutes of far (1°), middle (6°), and near (16°) sustained convergent fixation. Data were statistically analyzed with repeated-measures ANOVA. The main factor analyzed was the adapting vergence position (baseline, 16°, 6°, and 1°). Five minutes of sustained fixation significantly modified the phoria level [$F(3,27) = 43.69$; $P < 0.001$]. Post hoc analysis using a Bonferroni all pairwise test indicated that the baseline phoria measurement was significantly different from the phoria measured after a 1° and after a 16° sustained fixation task. The phoria after 1° fixation was more exophoric than the baseline measurement, and the phoria after 16° fixation was more esophoric than the baseline measurement.

Figure 8A shows the regression of baseline phoria compared with the adapted phoria level after 5 minutes of sustained fixation at 1°, 6°, and 16°. All 10 subjects (S1-S9, S11) showed changes in phoria after 5 minutes of sustained fixation located at three different fixations compared with the zero adaptation reference line. Figure 8B shows the correlation between baseline phoria and the amount of change in phoria adaptation. Correlation values for baseline phoria versus change in phoria (adapted minus baseline) after 1° ($r = 0.09$; $P = 0.81$), 6° ($r = -0.2$; $P = 0.56$), and 16° ($r = -0.33$; $P = 0.36$) sustained fixation were not significant. The average phoria changes with SD between baseline phoria and adapted phoria in all 10 subjects were $-1.74\Delta \pm 1.07\Delta$, $0.24\Delta \pm 1.95\Delta$, and $3.67\Delta \pm 0.91\Delta$ for far, middle, and near sustained fixation, respectively.

Discussion

Baseline Phoria and Phoria Adaptation Correlation with Vergence Peak Velocity Ratio

Phoria adaptation (change in tonic disparity vergence) modifies phoria toward the current state of fixation, presumably to

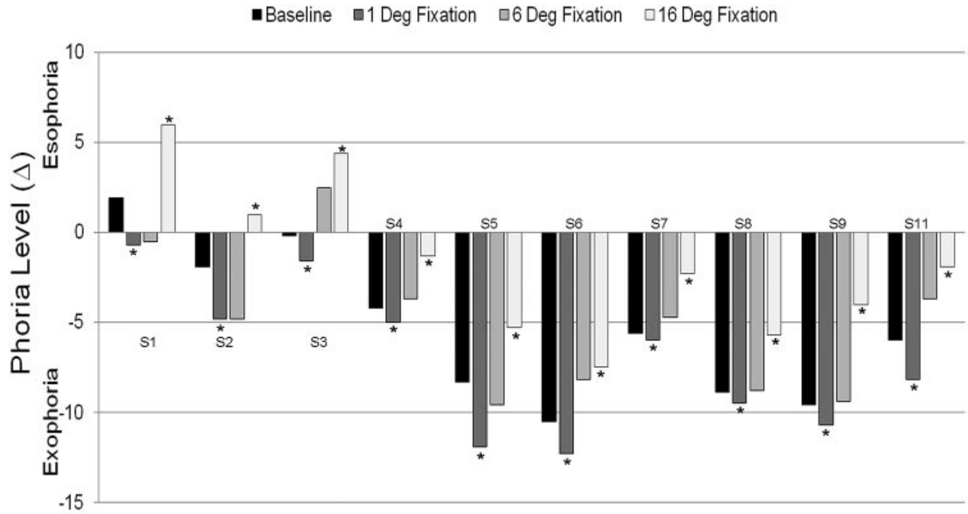

FIGURE 7. Summary of phoria adaptation results before adaptation or baseline after 5 minutes of the following: 1° of sustained fixation, after 6° of sustained fixation, and after 16° of sustained fixation using the limbus tracking system. Bonferroni all pairwise multiple comparison test showed that the baseline phoria was significantly different from the phoria measurement after 16° and 1° sustained fixation (*asterisks*).

reduce the load on disparity vergence (the dynamic disparity component).[30,31] Recent studies showed that convergence and divergence dynamics are modified after performing sustained tasks for different amounts of time at near and far. However, these studies did not report the subjects' baseline phoria or the amount of changes in phoria induced by phoria adaptation from the experimental tasks throughout the session.[1,15] Patel et al.[15] compared the peak velocity of the divergence and convergence fast vergence systems after 5 seconds of sustained fixation and after 30, 60, and 90 seconds of sustained fixation. They reported that peak divergence velocity was reduced by approximately 25% after 30 seconds of sustained vergence compared with only 5 seconds of sustained fixation.[15] They did not measure phoria directly, but other studies have shown that sustained fixation does vary or adapt the phoria level.[30] Furthermore, our laboratory has measured dissociated near phoria and divergence, and the results show that divergence peak velocity from the fast vergence system is correlated to the adapted phoria level.[31] However, our previous study did not investigate convergence, nor did it investigate a population with a range of baseline phoria levels. The present study measured both baseline phoria and adapted phoria levels after repetitive vergence steps located at different initial positions. These results show that the baseline and the adapted phoria measured after vergence steps are both highly correlated to the vergence peak velocity ratio. The novelty of the present study is that baseline and adapted phoria measured directly are correlated to convergence and divergence peak velocity asymmetries studied in a population of subjects with a range of phoria levels. Hence, phoria level should be a factor when investigating the asymmetries of peak velocity between the convergence and divergence subsystems.

Influence of Tonic Vergence, Accommodation, and AC/A Ratio on Phoria and Vergence Peak Velocity

The present study was conducted to investigate whether a correlation exists between phoria and peak velocity of convergence and divergence. Other factors to consider are tonic vergence, accommodation, and AC/A ratio. The phoria of a subject can be predicted quantitatively from the individual measures of dark vergence, accommodative response, and AC/A ratio.[32,33] Hence, dark vergence, accommodation, and the AC/A ratio should also be considered. Dark vergence is the resting state of the system when no stimulus is presented to either eye and may, in part, influence our results. Subject selection criteria included nonpresbyopes (our subjects were 21–29 years of age) and those who were emmetropes or had small refractive myopia (−1.5 D and −2 D in the present

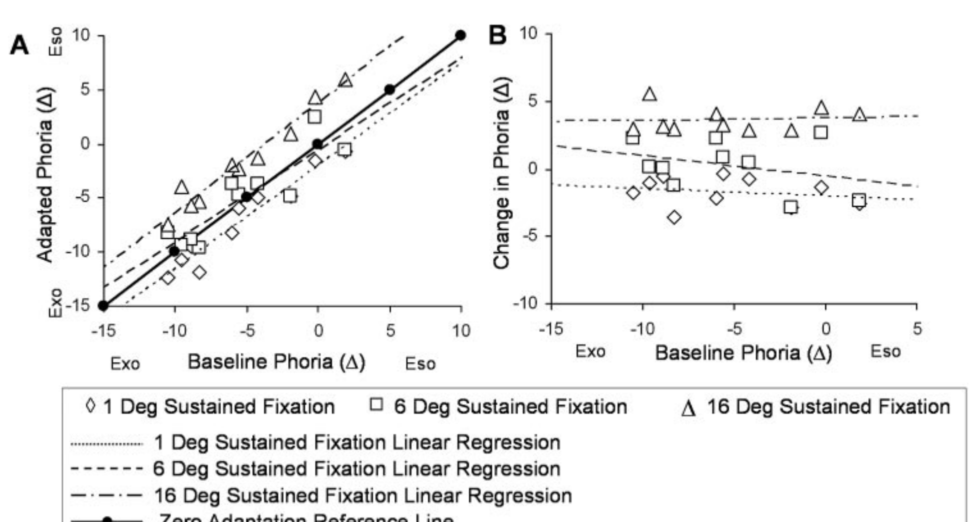

FIGURE 8. (**A**) Correlation between baseline and adapted phoria after 1°, 6°, and 16° sustained fixation. The zero adaptation reference line (*solid black line*) serves as a reference if no adaptation occurred or if the baseline phoria exactly equaled the phoria measured after sustained fixation. (**B**) Correlation of baseline phoria versus the change in phoria (the difference between adapted phoria and baseline phoria level.) Baseline phoria was not correlated to the change in phoria after 1°, 6°, or 16° sustained fixation.

study). For 8 of the 11 subjects, the AC/A ratios measured, and they were between 2:1 and 3:1. The AC/A ratios were consistent in this population and should not significantly influence the main outcome of this study.

Accommodation does influence disparity vergence but does not significantly influence the peak velocity of vergence. One study compared responses from a stimulus viewed through a pinhole that produced a disparity-only stimulus to responses located at two different physical positions.[16] The average peak velocity of the two responses (one with accommodative vergence and one without) were similar, as were the standard deviations of the peak velocity. The study further analyzed the temporal properties of SD and found that when accommodation was present, there was a secondary increase in SD approximately 100 to 200 ms after peak velocity from the step response. It was concluded that accommodative vergence begins approximately 100 to 200 ms after peak vergence velocity.[16] A pinhole eliminates the blur stimulus, but it is difficult to align, and subjects report difficulties in fusing the visual stimulus. However, our laboratory recently compared the peak velocity from three types of vergence step responses: a difference of Gaussian stimulus, which elicits vergence responses without any significant accommodative stimulation[34,35]; a line stimulus on a haploscope, which produces constant accommodative demand; and a vergence step stimulus using light-emitting diodes located at two different focal lengths from the subject's midline, which produces a strong change in accommodative demand. Our results show that the peak velocity from these responses was not significantly different and that changes in peak velocity in vergence were not from differences in accommodative stimuli.[31]

Future Direction for Vergence Models

Previous models have attempted to incorporate phoria to account for changes in disparity vergence responses, but these models do not accurately predict the influence of phoria on vergence dynamics or vice versa.[9,10] The present findings show that the role of phoria is more than a bias described by previous models. It may modify the dynamic controllers of both the convergence and the divergence systems. For instance, when an esophore converges, esophoria may enhance the convergence movement because of the natural tendency to move the eyes inward to its phoria position, resulting in faster convergence dynamics. This reduction in the static load presented to the controllers allows the controller to generate greater convergence dynamic behavior. However, when divergence is stimulated, an esophoric subject must inhibit the eye's natural tendency to rotate inward and then perform the movement, resulting in a reduction in divergence peak velocity. As a result, during the 4° vergence steps, an esophoric subject's convergence movements will be faster than the divergence movements, and the reverse will be true for exophoric subjects. Velocity ratio may also have an effect on the phoria.

Clinical Implications

Other studies suggest that the anatomy and physiology of the eye, or possibly the controller, determines a person's phoria level. Previous researchers have quantitatively analyzed the structure of the human extraocular muscle pulley systems and shown differences between persons that may lead to different phoria levels.[36] The ocular muscle proprioception is also reported to be involved in long-term maintenance of ocular alignment or phoria.[37] Clinical studies suggest that the cerebellum is involved in the control of vergence and the ability to perform phoria adaptation.[3] Clinical assessment of patients with convergence insufficiency and divergence insufficiency show increased exophoria and esophoria deviation at near, respectively.[38,39] Hence, the present study suggests that the person's phoria plays an important role within the vergence system. Future studies should account for baseline and the modifications of phoria during different visual tasks with respect to vergence dynamics. This will potentially lead to a better understanding of why some people are more susceptible to asthenopic symptoms and convergence or divergence insufficiencies.

Baseline Phoria Correlation to Phoria Adaptation

The first experiment showed that the baseline phoria was correlated to the vergence peak velocity ratio, but the change in phoria was not correlated to baseline phoria. However, the phoria was not significantly adapted after the series of the vergence steps located at different initial positions. Hence, a second experiment was conducted using a larger vergence range with a 5-minute sustained-fixation task to ensure that the phoria was significantly adapted. Results support significant changes in phoria compared with baseline after 5 minutes of sustained fixation at 16° and 1° binocular vergence demands. The goal of this experiment was to determine whether changes in phoria from extensive phoria adaptation induced by sustained fixation tasks were related to baseline phoria. For example, we hypothesized that esophores may show more phoria adaptation at far fixation than near fixation and that the reverse is true for exophores. However, our results showed that the change in phoria (adapted phoria − baseline phoria) was independent of the subject's baseline phoria level, indicating that phoria adaptation induced similar changes in phoria regardless of the baseline phoria level.

The independence of phoria change from baseline phoria has clinical implications. For example, patients with convergence insufficiency who often have asthenopic symptoms when performing near work have reduced phoria adaptation.[40] Consequently, if the phoria does not reduce the load of the vergence system during near or far tasks, the subject may be more susceptible to asthenopic symptoms because of an inability to adjust the phoria level. Hence, the ability to adjust the phoria level rather than baseline phoria may be a better indication of asthenopic symptoms.

In summary, this study showed that baseline phoria is a modulating factor in the relationship between convergence and divergence peak velocity dynamics and that baseline phoria was not correlated to the adaptive change in phoria for binocularly normal subjects. The implications of these results suggest that phoria should be incorporated in vergence models and that phoria and vergence dynamics should be measured when studying binocular dysfunctions such as convergence and divergence insufficiencies.

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