Variation of Binocular–Vertical Fusion Amplitude with Convergence

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Purpose. The maximum binocular vertical disparity that can be fused with disparity vergence (vertical-fusion amplitude or VFA), varies with convergence angle. VFA is larger for convergence responses to near than to far viewing distances; however, the clinical norms for changes in VFA with convergence have not been established. VFA at several convergence angles was measured to obtain a quantitative description of the changes in VFA with convergence.

Methods. Fifty-six adults took part in the study. Horizontal and vertical disparity stimuli were presented on a computer monitor by using the red-green anaglyphic technique. Stimulus to convergence was altered either by changing horizontal disparity on the computer monitor (experiment I: nine horizontal disparities: 1.2–22.5 PD [Δ]) or by changing the binocular viewing distance (experiment II: five viewing distances: 25–300 cm). Convergence was held constant during an experimental session, while vertical disparity was incremented in steps of 0.05 Δ after a subjective report of fusion, until the subject reported diplopia. The maximum vertical disparity that could be fused was defined as the VFA.

Results. VFA increased linearly over the range of convergence stimuli ($y = 0.10x + 1.62$) and intersubject variability of VFA increased marginally with the amount of convergence. Linear regression equations with similar slopes and *y*-intercepts were observed in experiments I and II.

Conclusions. The results of the experiments provide a quantitative description of a linear relationship between VFA and convergence. The linear regression equation could be used in a clinical setting to establish norms and to screen for vertical vergence abnormalities. (*Invest Ophthalmol Vis Sci.* 2007;48:1592–1600) DOI:10.1167/iovs.06-1018

Vertical retinal image disparities are encountered in several natural viewing conditions. For example, they are normally subtended by objects located in tertiary directions at finite viewing distances when the head and eyes are in primary position.[1] The vertical disparity, when quantified in a Fick coordinate system, increases with both azimuth and proximity of objects in space.[2] Under experimental viewing conditions, vertical disparities can be produced by a vertical prism (base-up or base-down) placed before one eye or by prismatic effects of a spectacle lens placed before one eye, such as in a correction for anisometropia.[1] Vertical disparity can be fused with a combination of motor fusion (vertical vergence) and sensory fusion that is described by the vertical dimension of Panum's fusional area.[3–7] Motor fusion of an experimentally induced vertical disparity is involuntary (i.e., it requires a disparity stimulus)[8] and it has a slow dynamic response.[4,9,10] The slow vertical vergence response compensates for approximately 80% to 85% of the disparity stimulus and the remaining 15% to 20% of fusion is brought about by a smaller sensory component.[4,9,11–14]

When compared to its horizontal counterpart, vertical vergence is limited in both speed[9,10,15] and amplitude[5,6,16] (see however, Howard et al.[17]). The maximum vertical disparity that can be fused (the vertical fusion amplitude [VFA]) is only approximately 3 to 5 Δ.[5,6] This is about five times less than the horizontal fusion amplitude (15–20 Δ) when measured under comparable viewing conditions.[18,19] However, there are several conditions under which larger VFAs have been observed. For instance, the VFA increases as the rate of incrementing vertical disparity decreases,[20] as the angular size of the fusion target increases,[8,13,20–23] and after orthoptic training.[24–27] Larger VFAs have also been noted in patients with long-standing or congenital superior oblique palsies.[28–30] Convergence can also change the VFA. Both circumstantial evidence[10,31] and quantitative investigation[4,32] support the finding that the VFA increases with convergence[4] and decreases with divergence.[32] Boman and Kertesz[32] measured the VFA with two convergence amplitudes (0 and 14.3 Δ of divergent disparity) and they found that the VFA of three of their four subjects decreased in the presence of the divergent disparity. Hara et al.[4] investigated the relationship between VFA and convergence from a far viewing distance (1.75 Δ vergence) to a near viewing distance (near convergence stimuli varied across different subjects from 10.5–26.8 Δ depending on their horizontal fusion capabilities). They observed an average VFA of 2.9 Δ at far viewing, which increased to 4.17 Δ at near viewing in 9 of their 12 subjects.

The change in VFA with convergence is not unexpected, given the increase in vertical disparity (in Fick coordinates) with target proximity.[2] However, it raises a pragmatic question. The population norm for VFA is 3 Δ.[5,33] This metric is used widely as a clinical norm to screen for patients with vertical vergence anomalies. However, this norm does not specify a convergence stimulus (or viewing distance) at which it applies, nor does it account for the change in VFA with convergence. This lack of specifications could lead to an ambiguity in the criteria for diagnosing vertical vergence anomalies that would depend on the viewing distance at which VFA is measured. Neither the circumstantial evidences of Gräfe[31] and Ygge[10] nor the quantitative investigations of Boman and Kertesz[32] and Hara et al.,[4] described for two convergence stimuli, provide enough information to determine a quantita-

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tive description of the coupling between the horizontal and vertical vergence amplitudes. Hence, the main purpose of this study was to obtain an analytical expression that describes the relationship between VFA and convergence, by measuring the VFA at several different convergence angles.

METHODS

The study was conducted at two different sites: the Elite School of Optometry, Chennai, India (experiment I), and the School of Optometry, University of California at Berkeley (experiment II). A total of 56 (30 in experiment I and 26 in experiment II) visually normal and healthy adults (mean age: 25.7 years; range, 17–46); males:females, 22:34) participated in the experiment. Two major races, Asian ($n = 41$) and white ($n = 11$), were represented in our experimental population. The mean refractive error of the subjects was -0.9 ± 2.0 D (range, $+1.50$ to -8.0 D) and the subjects wore their habitual refractive correction during the experiment. Subjects with anisometropia greater than 2.5 D were rejected from the experiment because differences in interocular retinal image size (aniseikonia) could hamper the subject's ability to fuse the horizontal and vertical disparities.[34] All experimental procedures adhered to the tenets of the Declaration of Helsinki and were approved by the Committee for Protection of Human Subjects (CPHS), University of California at Berkeley. All subjects underwent a routine optometric examination that screened for general visual health and integrity of binocular vision. Inclusion criteria included subjects with best-corrected visual acuity of 20/20 for distance and N6 for near, absence of any ocular disease or abnormal ocular motility, and distance and near horizontal phorias within the clinical norms.[35] None of the subjects had a vertical phoria at either a distance or near viewing distance.

Subjects fused a pair of red-green concentric circles while viewing them through red-green anaglyphic filters. The subject's head was restrained by a chin and a forehead rest. The red-green fusion targets were generated on a computer monitor using customized (MatLab; MathWorks, Natick, MA) extensions from the Psychophysics Toolbox.[36,37] Each concentric circle in the red-green pair subtended 0.38° (inner circle) and 2.15° (outer circle) of visual angle at a viewing distance of 50 cm. The luminance of the red and green pairs of concentric circles was similar to each other when they were viewed through the red and green filters, respectively (red concentric circles: 0.33 cd/m^2; green concentric circles: 0.45 cd/m^2). The luminance of each pair of concentric circles was approximately 10 times larger than the background luminance (the background luminance was 0.03 and 0.04 cd/m^2 when viewed through the red and green filters, respectively). The experiment was conducted in an otherwise darkened room, and the edges of the computer monitor were invisible to the observer. At the beginning of the experiment, the red-green circles were presented with a zero vertical disparity and a nonzero horizontal disparity. The horizontal disparity was randomly chosen from the range noted later in this paragraph and was fixed throughout the experiment session during which VFA was measured with the vertical disparity stimuli. After initiation of the session, the vertical disparity was incremented in steps of 0.05 Δ until the subject could not fuse the target and perceived vertical diplopia. The vertical disparity was incremented when the subject reported that the target was fused (single). VFA equaled the maximum vertical disparity that could be fused by the subjects before they perceived vertical diplopia. Similar experimental protocols have been used to measure the VFA.[4,6,9,20,34] The VFA at each convergence angle was measured thrice, and measures were averaged to obtain a mean VFA. Subjects were instructed to make the target single and report when the target appeared double. On completing a VFA measure, the subjects rested a few minutes before starting the next session, which had a different convergence angle. The convergence angle was randomly varied to minimize the possible influence of convergence on the vertical vergence adaptation.[38,39] VFAs at all convergence angles (noted below) were measured in a single sitting.

Convergence was stimulated differently in experiments I and II. In experiment I, the convergence stimulus was increased by reducing the horizontal separation between the red-green circles that were generated at a fixed viewing distance of 50 cm (Figs. 1a, 1b). The fixed viewing distance produced a constant stimulus to accommodation and the angular size of the target remained constant irrespective of the horizontal disparity. We investigated the VFA at nine different horizontal disparities (corresponding to nine simulated viewing distances: 600, 300, 200, 100, 75, 50, 40, 30, and 25 cm). These simulated viewing distances resulted from horizontal disparities of 1.2, 2.3, 3.5, 7.0, 9.3, 13.9, 17.3, 22.5, and 25.3 Δ, respectively. In experiment II, the horizontal disparity was increased by decreasing the viewing distance to the computer monitor (Figs. 1c, 1d). The horizontal separation between the red-green circles was adjusted to approximately half the subject's interpupillary distance, and the horizontal separation remained constant throughout the experiment. Both the accommodative stimulus and the angular size of the target increased with the convergence stimulus. The VFA was quantified at five different viewing distances (300, 200, 100, 50, and 25 cm) that resulted in mean convergence stimuli of 1.8, 3.1, 6.1, 12.2, and 24.4 Δ, respectively. In both experiments, the horizontal disparity was also scaled as a function of the subject's interpupillary distance, using equation 1. The horizontal disparities represent the mean horizontal disparity obtained by averaging the individual horizontal disparity stimuli at a given viewing distance:

$$\text{Horizontal disparity } (\Delta) = \text{interpupillary distance (cm)} \times [1/\text{viewing distance (m)}]$$

Vertical disparity is quantified in Helmholtz coordinates where natural targets in space always subtend zero vertical disparity, even when they are in tertiary directions at finite viewing distances.[2] Vertical disparity was determined by the combination of vertical separation between the red-green circles and viewing distance (Fig. 2). Since the viewing distance was held constant at 50 cm in experiment I, a given physical vertical separation corresponded to the same angular vertical separation in Helmholtz coordinates, irrespective of the convergence angle. However, in experiment II, because the viewing distance was changed systematically, a given physical vertical separation corresponded to a larger angular vertical separation at a proximal viewing distance than at a distal viewing distance. This was accounted for by scaling the physical vertical separation to produce the same angular vertical separation at all viewing distances.

All analyses were performed in two programs (MatLab; The MathWorks, and Excel; Microsoft, Redmond, WA). The VFAs were plotted as a function of the convergence angle for each subject, and the relationship between convergence and VFA was described by a linear regression equation. The convergence response is assumed to equal the convergence stimulus, although there are small discrepancies (fixation disparity) that are less than several minutes of arc.[40] Because the estimates of both the convergence response (x variable) and the VFA (y variable) were subject to measurement error, the linear regression equation was calculated by using an orthogonal (or reduced major axis) method, as opposed to the ordinary least-squares method.[41] The y-intercept of the linear regression equation describes the VFA at zero convergence angle (viewing distance of infinity) and the slope of the linear regression equation describes the change in VFA for a 1.0 Δ change in convergence. A group-linear regression equation was computed by grouping the data from all the subjects and plotting the VFA as a function of convergence angle (Δ). The robustness of the coefficients of this linear regression equation was assessed by computing the ±99% confidence intervals.[42] These analyses were performed separately on the data sets obtained from experiment I and II. However, as will be shown in the Results section, no significant differences were observed between the results of experiments I and II. Hence, the data obtained from the two experiments were pooled to obtain the overall group linear regression equation. Because the horizontal disparity

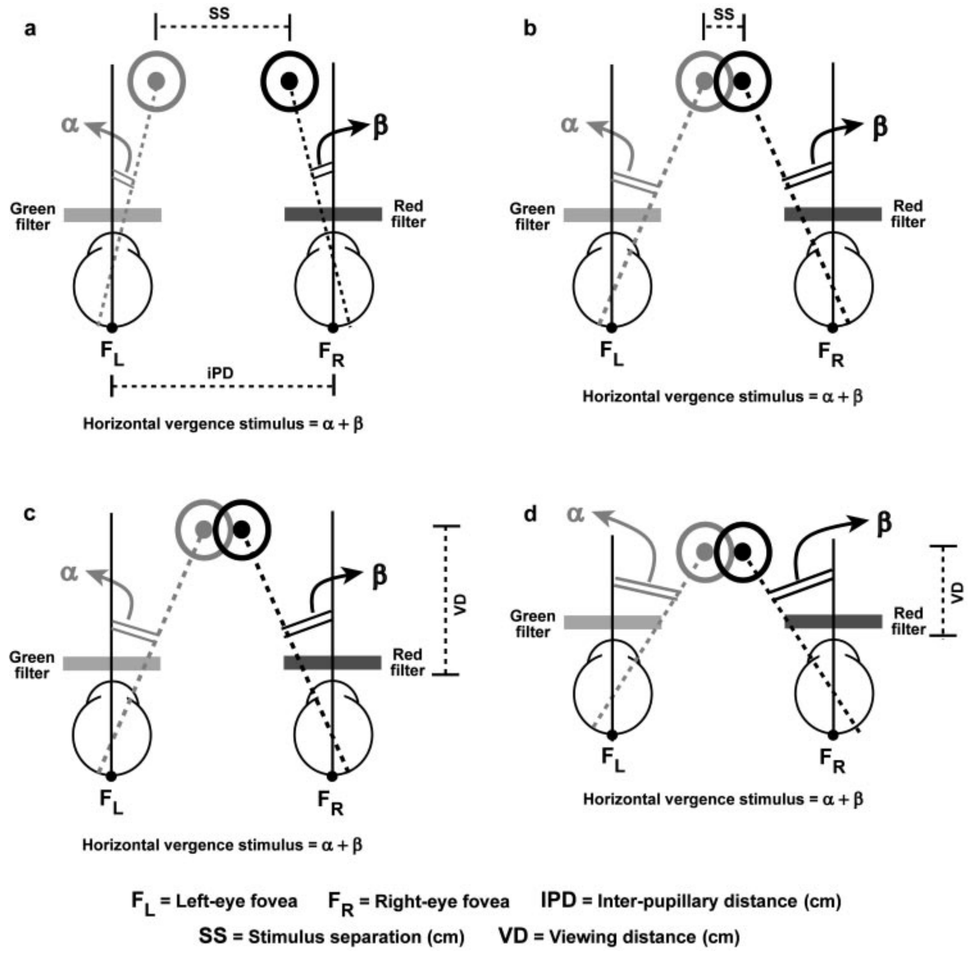

FIGURE 1. (**a**, **b**) Schema of two different convergence stimuli used in experiment I. The red-green concentric circles were generated on a computer monitor and their physical separation (SS) was reduced to increase the convergence stimulus (compare vergence angles in **a**, **b**). The convergence stimulus was larger in **b** than in **a**. (**c**, **d**) Schematic representation of two different convergence stimuli used in experiment II. The physical separation of the red-green concentric circles was fixed while the viewing distance (VD) was reduced to increase the convergence stimuli (compare vergence angles in **c**, **d**). The convergence stimulus was larger in (**d**) than in (**c**). The red concentric circle and red filter are shown in *black*, and the green concentric circle and green filter are shown in *gray*. These figures show the state of two eyes before convergence stimulus was fused. For the sake of clarity, the vertical vergence stimulus was 0 Δ in these figures.

stimuli (Δ) were scaled according to the IPD of the subject, a quantitative assessment of the intersubject variability of VFA using the raw data at a given horizontal disparity was not possible. Hence, the VFAs at 26 different convergence angles (0–25 Δ in 1-Δ steps) were computed from the subject's individual linear regression equation. The mean and the ±99% confidence intervals of the mean (accounting for ~2.5 SD about the mean in a normal distribution) was computed for each convergence angle.[42] These confidence intervals of the mean were intended to provide a quantitative estimate of the intersubject of the VFA at each convergence angle.

RESULTS

In the range of horizontal disparities that could be fused, all 30 subjects in experiment I and 22 subjects in experiment II showed an increase in the VFA with convergence (Figs. 3a, 4a). The data of each subject who showed an increase in VFA with convergence were described by a linear regression equation (r^2 range = 0.69–0.99) in experiment I (Fig. 3b, Table 1) and experiment II (Fig. 4b; thin grey lines, Table 2). The group linear regression equation obtained by plotting the data of all 30 subjects in experiment I was $y = 0.10x + 1.62$ ($r^2 = 0.34$; Fig. 3b; thick black line, Table 1). Similarly, the group linear regression equation obtained by plotting the data of 22 subjects in experiment II was $y = 0.09x + 2.05$ ($r^2 = 0.48$; Fig. 4b; thick black line, Table 2). The slope of the linear regression equation was significantly different from zero ($P < 0.01$) in both experiments, indicating that the VFA increased significantly with the convergence angle. The correlation of determination (r^2) was reduced in both group linear regression functions due to the intersubject variability. The robustness assessment of this linear regression fit resulted in narrow ±99% confidence interval bands (experiment I: $n = 153$, $df = 151$; experiment II: $n = 104$; $df = 102$) when compared to the variability in the raw data (Figs. 3b, 4b; black-dashed curves). This showed that, despite accounting for only 34% (experiment I) and 48% (experiment II) of the variance in the raw data, the group linear regression equations provided a robust fit to the raw data. The slopes and y-intercepts of the group linear regression equations obtained from experiments I and II were not significantly different from each other (slope $P > 0.5$; y-intercept $P > 0.5$).[43] This shows that the results obtained from experiment II were qualitatively and quantitatively similar to those obtained from experiment I.

Because the results of experiments I and II did not differ in any statistically significant manner (Fig. 5a), the data sets were combined to obtain an overall group linear regression equation that could be used in a clinical setting to screen for patients with vertical vergence abnormality. This linear regression equation ($y = 0.10x + 1.82$), along with the ±99% confidence intervals are shown in Figure 5b. Similar to the linear regression equations obtained from experiments I and II, the slope of the overall group linear regression equation was also significantly different from zero ($P < 0.01$). The correlation of determination ($r^2 = 0.38$) was reduced in the group linear regression function due to the intersubject variability. The robustness assessment of this linear regression fit resulted in narrow ±99% confidence interval bands (total number of samples = 257; $df = 253$) when compared to the variability in the raw data (Fig. 5b; black dashed lines). Figure 5c provides an

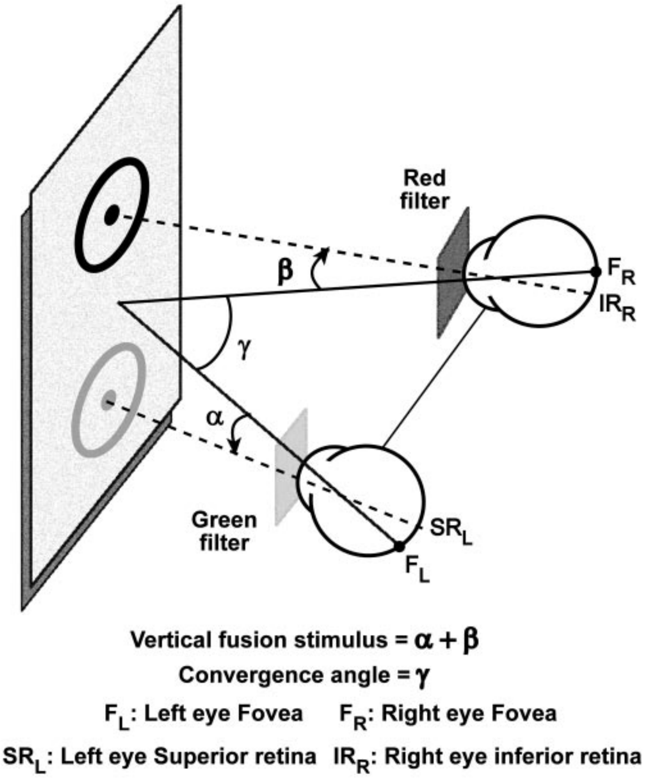

FIGURE 2. Schematic representation of a vertical disparity used in experiments I and II. The schema represents the positions of the eyes before fusing the vertical disparity. The vertical disparity stimulus is given by the sum of angles α and β. The convergence stimulus is given by angle γ. The red concentric circle and red filter are shown in *black*, and the green concentric circle and green filter are shown in *gray*. In the experiment, vertical disparities were generated by vertically displacing the red-green concentric circles in steps of 0.05 Δ.

estimate of the intersubject variability of VFA by plotting the mean ±99% confidence interval of the mean for each 1-Δ convergence bin. The ±99% confidence interval of the mean did not vary significantly with the convergence angle, and it ranged from ±0.31 to ± 0.50 Δ for vergence angles ranging from 0 to 25 Δ (Table 3).

Four subjects in experiment II did not follow this trend, and their data are shown separately in Figure 4a (solid black lines). These four subjects were re-examined at the UC Berkeley Optometry clinic for subtle binocular vision anomalies that went unnoticed during the screening procedures. All four subjects showed signs of intermittent tropias, microtropias and high AC/A ratios, and they were treated for their binocular vision anomalies using conventional clinical procedures. An attempt was made to re-examine all the other subjects who took part in experiment II. Some subjects were not available for re-examination, either because of relocation or lack of willingness to participate in the examination procedures. Of all the subjects re-examined, none showed any signs or symptoms of subtle binocular vision anomalies.

No significant differences in the results were observed when the data were grouped based on race (Asian or white; $P > 0.05$; data not shown) or gender ($P > 0.05$; data not shown).

Control Experiments

Two different control experiments were performed. As does convergence,[44] the vertical vergence system exhibits hysteresis after sustained periods of disparity stimulation.[33,45,46] For instance, Ogle and Prangen[33] observed that vertical vergence could respond to vertical disparities as large as 6 Δ within 3 to 10 minutes. The vertical vergence response persisted after one eye was occluded and is described as a vertical phoria adaptation. Similarly, based on the results of their prism adaptation experiment, Ohtsuki et al.[46] proposed that the reduction in vertical deviation in patients with superior oblique palsy could be related to the adaptable component of vertical vergence. Because in both experiments I and II, the vertical vergence stimulus was incremented only after subjects reported fusion of the targets, it raises the possibility that the VFA could be extended by a short-term adaptable component of vertical vergence. To test this possibility, experiment I was repeated on three subjects with the modification that the vertical disparities were incremented in steps of 0.05 Δ once every 6 seconds. Six seconds was assumed to be too short a duration for any significant adaptable compensation to occur. All other experimental conditions remained the same. Each subject showed a linear

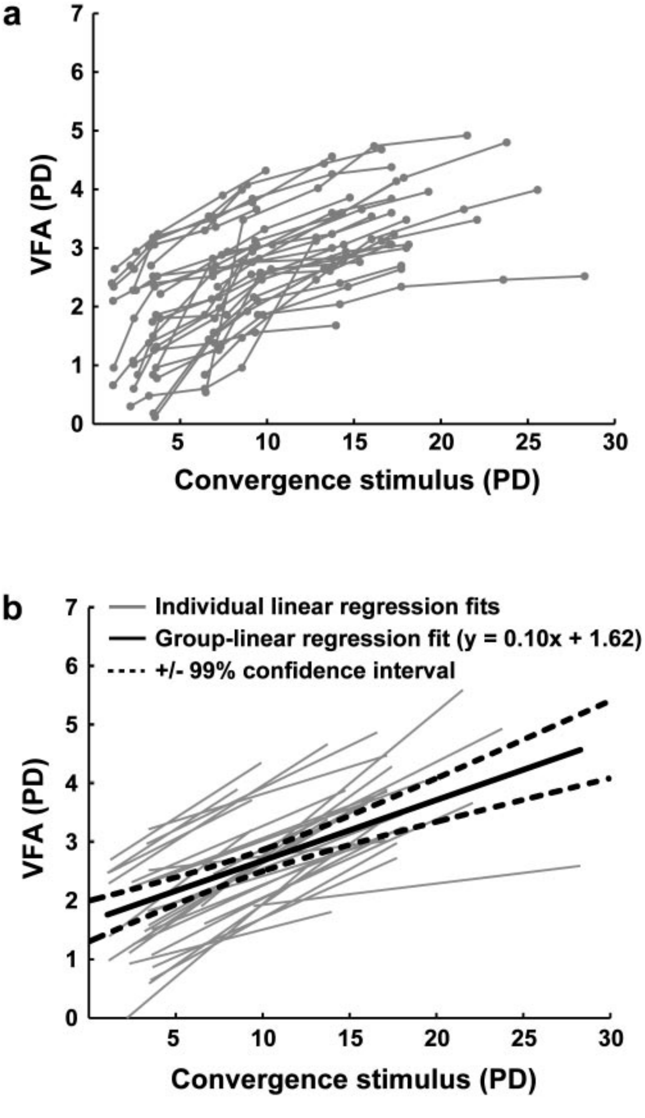

FIGURE 3. VFA plotted as a function of the convergence stimuli in individual subjects in experiment I. (**a**) Raw data of 30 subjects. (**b**) Linear regression equations fit to the raw data of these individual subjects (*thin gray lines*) along with the group linear regression equation fit (*thick black line*) and ±99% confidence intervals (*black dashed curves*). VFA increased linearly with the convergence angle in all 30 subjects.

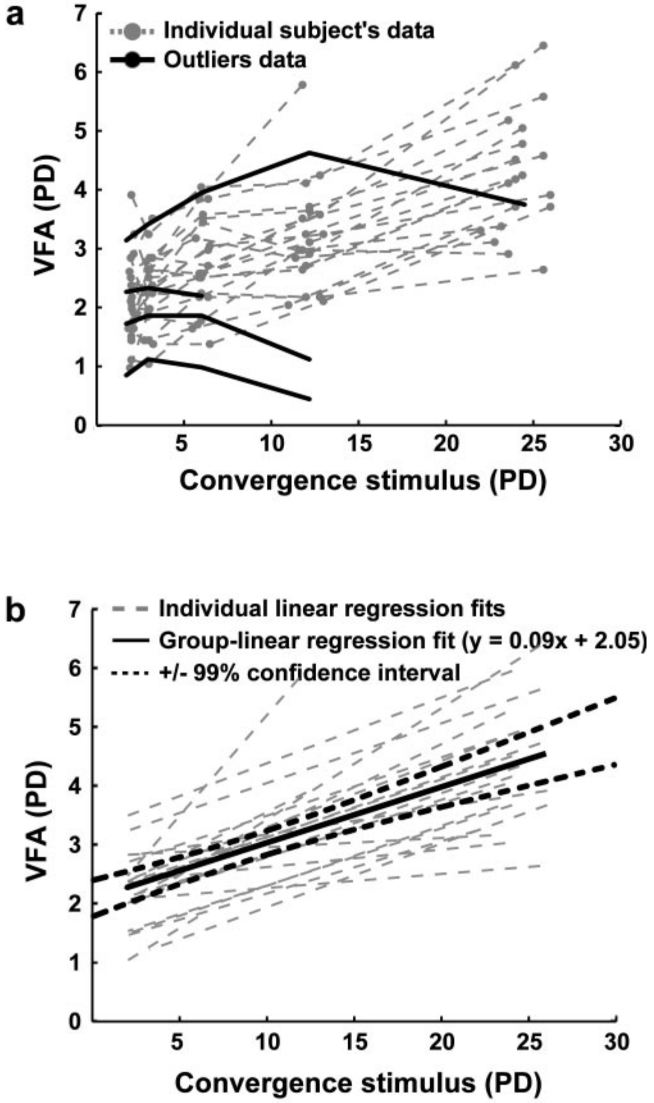

FIGURE 4. VFA plotted as a function of the convergence stimuli for individual subjects in experiment II. (**a**) Raw data of 22 subjects who showed an increase in VFA with convergence stimuli (*dashed gray lines*) along with the raw data of the four outliers (*solid black lines*). (**b**) Linear regression equations fit to the raw data of these 22 subjects (*dashed gray lines*) along with the group linear regression equation fit (*thick black line*) and ±99% confidence intervals (*black dashed curves*). The results of experiments I and II were qualitatively and quantitatively similar (compare Figs. 3 and 4).

increase in VFA with convergence angle. These results are similar to those obtained in experiment I and were also similar to those obtained by Hara et al.[4] For each subject, the slope and *y*-intercept of the linear regression equation obtained in the control experiment was compared with the respective slope and *y*-intercept obtained in experiment I for statistically significant differences.[43] The difference in slopes and *y*-intercepts were statistically nonsignificant ($P > 0.5$) in all three subjects (data not shown). These results suggest that the adaptable component of vertical vergence is unlikely to influence the VFAs significantly.

The second control experiment was designed to eliminate the possibility that the increase in VFA with convergence was somehow related to the way that horizontal disparity was varied in experiments I and II. In both experiments, vertical disparities were produced by symmetrically and simultaneously displacing the right eye image upward and the left eye image downward (right hyperdisparity). We tested whether VFA depends on the sign of the vertical disparity in three subjects by comparing responses to a right hyperstimulation paradigm and a left hyperstimulation paradigm (displacing the left eye image upward and the right eye image downward). All other experimental conditions remained the same. Each subject showed a linear increase in VFA with convergence angle in both the left hyper- and the right hyperstimulation paradigms. For each subject, the slopes and *y*-intercepts of linear regression equations obtained in the left hyper- and the right hyperparadigm were compared for statistically significant differences.[43] The difference in slopes and *y*-intercepts were statistically nonsignificant ($P > 0.5$) in all three subjects (data not shown). Hence, for those three subjects, the data from the two experiments were combined, and the averaged values were used for the analyses. Similar results were obtained by Ogle and Prangen[33] when they measured the VFAs to right and left hyperdisparity paradigms using the vertical fixation–disparity technique.

DISCUSSION

The main purpose of this experiment was to develop a quantitative description of coupling between VFA and convergence. We measured the VFA during several (maximum of nine) con-

TABLE 1. The Individual Orthogonal Linear Regression Equation Fit to the Data of VFA Plotted as a Function of Convergence Stimulus Obtained from Experiment I

Subjects	Linear Regression Equation	r^2	P
1	$y = 0.16x + 0.12$	0.94	<0.002
2	$y = 0.19x + 2.27$	0.95	<0.002
3	$y = 0.09x + 1.52$	0.93	<0.003
4	$y = 0.11x + 1.96$	0.97	<0.001
5	$y = 0.25x - 0.55$	0.82	<0.01
6	$y = 0.19x + 2.08$	0.93	<0.002
7	$y = 0.13x + 0.38$	0.98	<0.001
8	$y = 0.04x + 1.57$	0.91	<0.003
9	$y = 0.25x + 0.32$	0.69	<0.03
10	$y = 0.09x + 2.90$	0.97	<0.001
11	$y = 0.11x + 1.93$	0.97	<0.001
12	$y = 0.14x + 2.49$	0.91	<0.004
13	$y = 0.12x + 1.07$	0.93	<0.002
14	$y = 0.21x + 0.62$	0.94	<0.002
15	$y = 0.17x + 1.00$	0.73	<0.02
16	$y = 0.22x + 1.13$	0.85	<0.05
17	$y = 0.19x + 2.46$	0.99	<0.001
18	$y = 0.13x + 2.00$	0.99	<0.001
19	$y = 0.17x + 0.93$	0.94	<0.003
20	$y = 0.19x + 0.76$	0.88	<0.01
21	$y = 0.08x + 0.75$	0.71	<0.02
22	$y = 0.15x + 0.53$	0.84	<0.01
23	$y = 0.15x + 2.31$	0.93	<0.002
24	$y = 0.13x + 0.92$	0.80	<0.01
25	$y = 0.15x + 1.38$	0.99	<0.001
26	$y = 0.12x + 1.40$	0.99	<0.001
27	$y = 0.17x + 0.06$	0.83	<0.01
28	$y = 0.04x + 2.39$	0.95	<0.002
29	$y = 0.21x - 0.13$	0.92	<0.002
30	$y = 0.13x + 0.72$	0.96	<0.001
Mean	$y = 0.10x + 1.62$	0.33	

The percentage variance described by the linear regression equation is given by r^2 in column 3. The probability describing the statistical significance of the slope of the individual linear regression equations is given in column 4. Small probabilities indicate that, in most of the subjects, the slope of the linear regression equation was significantly different from zero.

Table 2. The Individual Orthogonal Linear Regression Equation Fit to the Data of VFA Plotted as a Function of Convergence Stimulus Obtained from Experiment II

Subjects	Linear Regression Equation	r^2	P
1	$y = 0.10x + 1.82$	0.99	<0.001
2	$y = 0.05x + 2.70$	0.63	<0.05
3	$y = 0.09x + 1.93$	0.95	<0.001
4	$y = 0.19x + 1.53$	0.98	<0.001
5	$y = 0.11x + 3.26$	0.87	<0.01
6	$y = 0.02x + 2.79$	0.33	<0.13
7	$y = 0.19x + 0.66$	0.89	<0.005
8	$y = 0.11x + 0.85$	0.98	<0.001
9	$y = 0.10x + 2.15$	0.99	<0.001
10	$y = 0.10x + 1.33$	0.93	<0.003
11	$y = 0.10x + 2.50$	0.87	<0.007
12	$y = 0.10x + 3.02$	0.96	<0.01
13	$y = 0.15x + 2.07$	0.77	<0.02
14	$y = 0.11x + 2.16$	0.83	<0.01
15	$y = 0.10x + 2.10$	0.88	<0.007
16	$y = 0.15x + 1.79$	0.95	<0.002
17	$y = 0.10x + 1.28$	0.82	<0.01
18	$y = 0.10x + 1.80$	0.82	<0.01
19	$y = 0.34x + 1.79$	0.99	<0.001
20	$y = 0.02x + 2.01$	0.77	<0.02
21	$y = 0.03x + 2.31$	0.30	<0.14
22	$y = 0.09x + 1.27$	0.95	<0.001
Mean	$y = 0.09x + 2.05$	0.48	

The data of four outliers that could not be fit with linear regression equations are not shown. The data shown are as described in Table 1.

Table 3. The Mean and ±99% Confidence Interval of the Mean of the VFAs at Each 1-Δ Convergence Bin

Convergence Stimulus (Δ)	Mean VFA (Δ)	±99% CI (Δ)
0	1.54	0.31
1	1.68	0.30
2	1.81	0.29
3	1.94	0.29
4	2.08	0.28
5	2.21	0.28
6	2.34	0.28
7	2.48	0.28
8	2.61	0.28
9	2.74	0.28
10	2.87	0.29
11	3.00	0.30
12	3.14	0.30
13	3.27	0.31
14	3.40	0.33
15	3.54	0.34
16	3.67	0.35
17	3.80	0.36
18	3.94	0.38
19	4.07	0.39
20	4.20	0.41
21	4.33	0.43
22	4.47	0.44
23	4.60	0.46
24	4.73	0.48
25	4.86	0.50

The mean ±99% confidence interval was obtained by averaging the individual linear regression equation-estimated VFA obtained from 52 subjects. This calculation provides a quantitative estimate of the intersubject variability of VFA at different convergence bins.

vergence angles. The results of experiments I and II show that the VFA increases with convergence in 52 of 56 subjects tested (Figs. 3a, 4a, 5a). These results, both qualitatively and quantitatively, confirm the findings of earlier experiments[4,10,31,32] and extend their results by showing that, in the range of our convergence stimuli, VFA increased linearly with convergence (Figs. 3b, 4b, 5b). The group linear regression equations obtained from experiments I and II were $y = 0.10x + 1.62$ (Fig. 3b) and $y = 0.09x + 2.05$ (Fig. 4b), respectively. The linear regression equation obtained by pooling the data of experi-

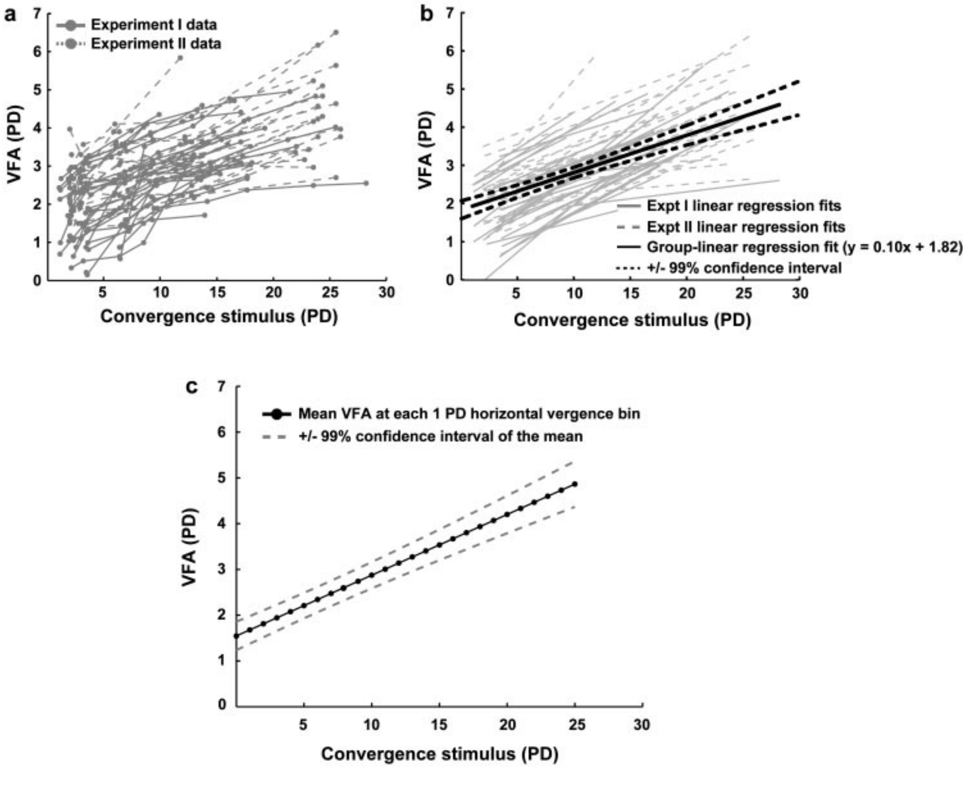

Figure 5. Pooled data from experiments I and II. (**a**) Raw data of 52 subjects who showed an increase in VFA with convergence. (**b**) Linear regression equations fit to the raw data of these individual subjects (*solid gray* and *dashed gray lines*) along with the group linear regression equation fit (*thick black line*) and ±99% confidence intervals (*black dashed curves*). (**c**) The mean (*black line*) and ±99% confidence interval of the mean (*dashed gray lines*) of the VFAs at each 1-Δ convergence bin. The mean and ±99% confidence interval was obtained by averaging the individual linear regression equation estimated VFA obtained from 52 subjects.

ment I and II was $y = 0.10x + 1.82$ (Fig. 5b). The coefficients of the linear regression equation were very robust to the intersubject variability as evidenced the narrow ±99% confidence intervals (Fig. 5b). Furthermore, the linear regression equation did not vary significantly with the experimental condition (experiments I and II and the two control experiments), race, or gender.

All components of the oculomotor system (e.g., horizontal disparity vergence[47] and ocular accommodation[48]) are characterized by the presence of significant intra- and intersubject variability. Variability could either have a biological origin or it could be introduced by external factors such as those related to measurement. Although the exact source of variability was not systematically investigated in our experiment, the data showed that the VFA exhibits a small amount of intersubject variability (Fig. 5c). This interindividual variability when expressed in terms of the ±99% confidence intervals (Fig. 5c; Table 3) indicates that, for a given convergence angle (within 0–25 Δ), the VFAs of our subjects are likely to fall within the range 99% of times. For instance, among the 52 subjects tested, the magnitude of inter-subject variability (estimated from the 99% confidence interval of the mean) was approximately one fifth, one eleventh, and one tenth of the mean VFAs at 0, 14, and 25 Δ of convergence respectively (Fig. 5c). The intersubject variability also remained fairly constant (0.31–0.50 Δ) across a large range of convergence angles (0–25 Δ; Fig. 5c, Table 3). As noted earlier, although the intersubject variability did reduce the correlation of determinant (r^2) between the VFA and convergence (Figs. 3b, 4b, 5b), its influence on the robustness of the group average linear regression equations was minimal as evidenced by the narrow ± 99% confidence intervals (Figs. 3b, 4b, 5b). The correlation of determinant of the individual linear regression equations was also high (range, 0.99–0.71). Taken together, these observations suggest that the VFA is tightly coupled with the convergence response and that this coupling is minimally influenced by the intersubject variability.

The population distributions of vertical phorias at far (~20 ft.) and near (~13 in.) are very similar to each other,[49,50] with the mean vertical phoria close to 0 Δ at both viewing distances.[49,51,52] The similarity in distributions is retained even when the distributions are only composed of patients with clinically significant (>0.5 Δ) distance and near vertical phorias.[50] The increase in VFA with convergence predicts that the vertical vergence system possesses greater capacity to compensate for vertical phorias at near than at far viewing distances. A constant vertical phoria would thus present a smaller demand on the vertical fusional vergence system at near than at far viewing distances. This could reduce the incidence of symptoms associated with vertical phorias (e.g., headache, asthenopia) at near compared with far viewing distances. The magnitude of vertical tropias presented under binocular viewing conditions could be smaller at near viewing distances than at far viewing distances if the fusional vertical vergence attempted to reduce the tropia. Indeed, Ohtsuki et al.[46] observed that in a group of 84 patients with superior oblique palsy, 23 had smaller vertical deviations at a near viewing distance than at a far viewing distance. In another study, Gräf et al.[53] found that in a group of 19 patients with superior oblique palsy, the amplitude of vertical deviation decreased with viewing distance in 4 patients. The remaining patients (61 patients in Ohtsuki et al.[46] and 15 in Graf et al.[53]) in both studies either showed the opposite pattern of vertical deviation with viewing distance. Vertical deviation was smaller at far than near viewing distances or showed no difference in vertical deviation between near and far. Based on the results of their prism-adaptation experiment, Ohtsuki et al.[46] proposed that the more typical reduction of vertical deviation at near could be explained in part by an adaptive component of vertical vergence, which could be stimulated by attempted efforts of binocular vertical motor fusion.[54] The results for the remaining patients in both these studies contradict this prediction. However, the results for these patients are rendered inconclusive due to the nonhomogeneity in the pathophysiology of superior oblique palsy observed in these patients.

Hara et al.[4] showed that the increase in VFA with convergence is brought about by an increase in the motor component of vertical vergence. The exact reason for the increase in the motor component of VFA with convergence remains unanswered. Although the experiments that we performed do not provide an answer, they exclude three plausible explanations that are worth considering. First, it has been shown by several authors that the VFA increases with the size of the fusion target.[8,20–23] It is plausible that the concurrent increase in angular size of the fusion target with the target proximity, as was the case in experiment II, was responsible for the increase in VFA with convergence. However, the increase of VFA with convergence also occurred when the angular size of the fusion target remained independent of the convergence stimulus, as was the case in experiment I. Hence, it is unlikely that the increase in angular size of the fusion target with convergence is responsible for the increase in VFA. Second, because both experiments I and II delayed the increase in vertical disparity until subjects reported fusion, the adaptable component of the vertical vergence system could have increased the VFA.[33,39,46] Larger VFAs have been observed by Ogle and Prangen[33] after vertical prism adaptation. Control experiment II was performed on three subjects to rule out this factor. At each convergence position, the VFA was estimated by incrementing the vertical vergence stimulus once every 6 seconds, thus providing minimal time for any short-term adaptation to occur. No statistically significant differences were observed between the results of control experiment II and the main experiment I ($P > 0.05$). The results of both control experiment II and main experiment I also compare well with the results obtained by Hara et al.[4] who estimated the VFA by incrementing the vertical vergence stimulus once every 6 seconds. These results suggest that the adaptable component of the vertical vergence system could play only a minor role in increasing the VFA with convergence angle. Third, since naturally occurring vertical disparities (in Fick coordinates) are encountered more often during near viewing than during distance viewing,[2] it is plausible that the increase in VFA at near viewing is related to accommodation or to the sense of proximity of the fusion targets.[15] In experiment I, the accommodative stimulus was held constant and the horizontal disparities were generated by changing the horizontal separation between the red-green circles on a computer monitor placed at 50 cm in front of the subject. The increase in VFA with convergence in experiment I obtained with a constant accommodative stimulus suggests that accommodation is a minor determinant in the coupling between VFA and convergence. The sense of proximity was not explicitly controlled in either of our experiments. In experiment II, convergence was stimulated by changing the physical distance between the subject and the horizontal fusion targets. The increase in physical proximity and the increase in retinal image size of the fusion targets could provide a proximal cue to the vertical vergence system. In experiment I, the horizontal disparities were generated on a computer monitor that was placed at 50 cm in front of the subject. Although weak and ineffective in the presence of other visual and nonvisual cues,[55–57] it is plausible that the proprioceptive signals generated by the horizontal recti muscles during convergence could have provided the desired sense of proximity to the vertical vergence system. Prior studies have shown that proximal cues such as motion parallax and overlap are ineffective in stimulating vertical vergence.[39] Whether the sense of proximity plays a role in the increase in VFA with convergence remains a question; however, given the robustness of the effect observed here, it seems unlikely that the sense of proximity could solely account for the coupling between VFA and convergence. Vertical vergence eye movements that have been trained to change in association with convergence are thought to be preprogrammed (and under adaptive recalibration), based on an internally generated three-dimensional motor map.[2,15,38] The increase in VFA with convergence could result from a similar preprogrammed cross-link whose gain is analogous to the cross-link gains between accommodation and convergence (AC/A[58,59] and CA/C[60,61] ratios).

In its current state, the population norm for VFA (VFA should be greater than or equal to 3 Δ[5,33]) neither specifies a viewing distance at which this norm is applicable nor does it specify a rate of increase in VFA with convergence.[5,33] We found in a group of 52 individuals that the VFA increases with convergence angle and this increase could be described by a linear regression equation (VFA = 0.10 × convergence angle + 1.82; Fig. 5b). The slope of the linear regression equation describes the rate of increase in VFA with convergence, and the *y*-intercept describes the VFA at a viewing distance of infinity. The VFA norm equals the VFA predicted by our regression equation at a convergence angle of 11 Δ (or at a binocular viewing distance of 67 cm assuming an IPD of 6.1 cm). For viewing distances closer than 67 cm, the VFA norm is smaller than that predicted by our regression equation and for viewing distances farther than 67 cm, the VFA norm is larger than that predicted by our regression equation (Fig. 5b, Table 3). This suggests that if the VFA norm is used in its current state, it could lead to systematic errors in the diagnosis of vertical vergence abnormalities. For instance, at binocular viewing distances closer than 67 cm, the VFA norm tends to underestimate the individual's maximum vertical vergence capability, thus reducing the chances of diagnosing a vertical vergence abnormality. The reverse would be true at binocular viewing distances farther than 67 cm. Furthermore, the VFA norm would be rendered ineffective as a diagnostic metric when the VFA changes between distance viewing (∼6 m) and near viewing (∼40 cm). Based on these observations, it seems more appropriate to use the linear regression equation developed in our experiment in lieu of the existing VFA population norm to aid the clinician in making a diagnosis of vertical vergence abnormalities. The interindividual variability of VFAs noted in our experiment shows that a range of VFAs can be expected at any given viewing distance (Figs. 5b, 5c). Although small, it is appropriate to account for this variability by characterizing the population norm at a given convergence angle by a range of values instead of a single number. This range is provided by the ± 99% confidence intervals shown in Figure 5c and Table 3 for a range of convergence angles (within 0–25 Δ).

CONCLUSIONS

The increase in VFA with convergence has been investigated previously with only two convergence amplitudes.[4,32] This precludes a quantitative description of the relationship between the VFA and convergence angle. We measured the VFA at nine different convergence angles and described the relationship between VFA and convergence response by using a simple linear regression equation that was very robust to intersubject variability. It did not show any significant changes with experimental condition, race, or sex. The linear regression equation developed could be used as a population norm equation for VFA in lieu of the existing single VFA value that does not account for the change in VFA with convergence (or binocular viewing distance).

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