Published in final edited form as:

Invest Ophthalmol Vis Sci. 2007 April ; 48(4): 1592–1600.

Variation of binocular-vertical fusion amplitude with convergence

Shrikant R. Bharadwaj^{1,2,*}, Pia M. Hoenig¹, C. V. Sivaramakrishnan², B. Karthikeyan², Donna Simonian¹, Katie Mau¹, Sally Rastani¹, and Clifton M. Schor¹

¹ School of Optometry, University of California at Berkeley, Berkeley, CA – 94720 USA

² Elite school of Optometry, Medical Research Foundation, Chennai, Tamil Nadu – 600018 India

Abstract

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— 56-adults took part in the study. Horizontal and vertical disparity stimuli were presented on a computer monitor using the red-green anaglyphic technique. Stimulus to convergence was altered either by changing horizontal disparity on the computer monitor (experiment I: 9 horizontal disparities: 1.2 – 22.5 Δ) or by changing the binocular viewing distance (experiment II: 5 viewing distances: 25 – 300 cms). 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 inter-subject 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 our experiments provide a quantitative description of a linear relationship between VFA and convergence. The linear regression equation could be employed in a clinical setting to establish norms and screen for vertical vergence abnormalities.

Keywords

vertical vergence; convergence; viewing distance; clinical norm; binocular fusion

1. Introduction

Vertical retinal-image disparities are encountered under a number of 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 position¹. The vertical disparity, when quantified in a Fick coordinate system, increases with both azimuth and proximity of objects in space². Under experimental viewing conditions, vertical disparities can be produced by a vertical prism (base-up or a base-down) placed before one eye or by prismatic effects of a spectacle lens placed before one eye such as in a correction for anisometropia¹. Vertical disparity can be fused with a combination of motor fusion (vertical vergence) and

Corresponding author: Shrikant R. Bharadwaj PhD, School of Optometry, 800 E Atwater Avenue, Bloomington, IN – 47405, E-mail: srbharad@indiana.edu, Telephone: (812) 345 – 9835, Fax: (812) 855 – 7045.

*Present address: School of Optometry, Indiana University at Bloomington, Indiana – 47405

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 about 80 – 85% of the disparity stimulus and the remaining 15 – 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, Allison and Zacher¹⁷). The maximum vertical disparity that can be fused [the vertical fusion amplitude (VFA)] is only about 3 – 5 Δ ^{5,6}. This is about five-fold less than the horizontal fusion amplitude (15 – 20 Δ) when measured under comparable viewing conditions^{18,19}. However, there are a number of conditions under which larger VFA's have been observed. For instance, the VFA increases as the rate of incrementing vertical disparity decreases²⁰, as the angular size of fusion target increases^{8,13,20–23}, and following orthoptic training^{24–27}. Larger VFA's have also been noted in patients with long-standing or congenital superior oblique palsies^{28–30}. Convergence can also change the VFA. Both circumstantial evidences^{10,31} and quantitative investigations^{4,32} report that the VFA increases with convergence⁴ and it decreases with divergence³². Boman and Kertesz³² measured the VFA with two convergence amplitudes (0 and 14.3 Δ of divergent disparity). They found the VFA of three of their four subjects decreased in the presence of the divergent disparity. Hara et al⁴ 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 Δ – 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 nine of their twelve subjects.

The change in VFA with convergence is not unexpected, given the increase in vertical disparity (in Fick coordinates) with target proximity². 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 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 Gräfe³¹ and Ygge¹⁰ nor the quantitative investigations of Boman and Kertesz³² and Hara et al⁴, described for two convergence stimuli, provide enough information to determine a quantitative description of the coupling between the horizontal and vertical vergence amplitudes. Hence, the main aim of this experiment was to obtain an analytical expression for the relationship between VFA and convergence by measuring the VFA at a number of different convergence angles.

2. Methods

This study was conducted at two different sites; one, at the Elite School of Optometry, Chennai, India (experiment I) and two, at 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 yrs (range: 17 – 46 yrs); males: females = 22: 34] participated in the experiment. Two major races, Asian (n = 41) and Caucasian (n = 11), were represented in our experimental population. The mean refractive error of the subjects was $-0.9 \text{ D} \pm 2.0 \text{ D}$ (range: +1.50 D 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 for differences in inter-ocular retinal-image size (aniseikonia) could hamper the subject's ability to fuse the horizontal and vertical disparities³⁴. 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 pathology or abnormal ocular motility, and distance and near horizontal phorias within the clinical norms³⁵. 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)[®], 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 cms. The luminance of red and green pair 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/m²; green concentric circles: 0.45 cd/m²). The luminance of each pair of concentric circles was approximately ten times larger than the background luminance (the background luminance was 0.03 cd/m² and 0.04 cd/m² when viewed through the red and green filter 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 non-zero horizontal disparity. The horizontal disparity was randomly chosen from the range noted below and was fixed throughout the experiment session during which VFA was measured with the vertical disparity stimuli. Following 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 in the past 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. Upon completing a VFA measure, the subjects rested a few minutes prior to starting the next session that had a different convergence angle. The convergence angle was randomly varied in order to minimize the possible influence of convergence on the vertical vergence adaptation^{38,39}. VFA's 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 cms (Figure 1a, b). 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 cms). 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 (Figure 1c, d). The horizontal separation between the red-green circles was adjusted to approximately half the subject's inter-pupillary distance and the horizontal separation remained constant throughout the experiment. Here, 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 cms) 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 inter-pupillary distance using equation 1. The horizontal disparities reported above represent the mean horizontal disparity obtained by averaging the individual horizontal disparity stimuli at a given viewing distance.

$$\text{Horizontal disparity}(\Delta) = \text{Inter - pupillary distance (Cms)} \times [1 / \text{Viewing distance (M)}]$$

Eq 1

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 distances². Vertical disparity was determined by the combination of vertical separation between the red-green circles and viewing distance (Figure 2). Since the viewing distance was held constant at 50cm 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, since 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 in order to produce the same angular vertical separation at all viewing distances.

All analyses were performed using Matlab[®] and Microsoft Excel[®]. The VFA's were plotted as a function of the convergence angle for each individual subject and the relationship between convergence and VFA was described using 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 arc⁴². Since 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 using an orthogonal (or reduced major axis) method as opposed to the ordinary least squared method⁴⁰. 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 $\pm 99\%$ confidence intervals⁴¹. 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 experiment I and II. Hence the data obtained from the two experiments were pooled together to obtain the overall group-linear regression equation. Because the horizontal disparity stimuli (Δ) were scaled according to the IPD of the subject, a quantitative assessment of the inter-subject variability of VFA using the raw-data at a given horizontal disparity was not possible. Hence, the VFA's 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 $\pm 99\%$ confidence intervals of the mean (accounting for approximately 2.5-standard deviations about the mean in a normal distribution) was computed for each convergence angle⁴¹. These confidence intervals of the mean were intended to provide a quantitative estimate of the inter-subject of the VFA at each convergence angle.

3. 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 (Figure 3a, 4a). The data of each subject who showed an increase in VFA with convergence was described by a linear regression equation (r^2 range = 0.69 – 0.99) in both experiment I (Figure 3b, Table I) and experiment II (Figure 4b; thin blue lines, Table II). The group-linear regression equation obtained by plotted the data of all 30 subjects in experiment I was $y = 0.10x + 1.62$ ($r^2 = 0.34$) (Figure 3b; thick black line, Table I). Similarly, the group-linear regression equation obtained by plotting the data of 22 subjects in experiment II was $y = 0.09x + 2.05$ ($r^2 = 0.48$) (Figure 4b; thick black line, Table II). The slope of the linear regression equation was significantly different from zero (p-value: <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 inter-subject variability. The robustness assessment of this linear regression fit resulted in narrow $\pm 99\%$ confidence interval bands (experiment I: $n = 153$, $dof = 151$; experiment II: $n = 104$; $dof = 102$) when compared to the variability in the raw data (Figure 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 statistically insignificantly different from each other (slopes p-value: >0.5 ; y-intercepts p-value: >0.5)⁴². This shows that the results obtained from experiment II were both qualitatively and quantitatively similar to those obtained from experiment I.

Since the results of experiment I and II did not differ in any statistically significant manner (Figure 5a), the data-sets were combined to obtain an overall group-linear regression equation that could be employed in a clinical setting to screen for patients with vertical vergence abnormality. This linear regression equation ($y = 0.10x + 1.82$) along with the $\pm 99\%$ 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 statistically significantly different from zero (p-value: <0.01). The correlation of determination ($r^2 = 0.38$) was reduced in the group-linear regression function due to the inter-subject variability. The robustness assessment of this linear regression fit resulted in narrow $\pm 99\%$ confidence interval bands (total number of samples = 257; degrees of freedom = 253) when compared to the variability in the raw data (Figure 5b; black dashed curves). Figure 5c provides an estimate of the inter-subject variability of VFA by plotting the mean $\pm 99\%$ confidence interval of the mean for each $1-\Delta$ convergence bin. The $\pm 99\%$ confidence interval of the mean did not vary significantly with the convergence angle and it ranged from $\pm 0.31 \Delta$ to $\pm 0.50 \Delta$ for vergence angles ranging from $0 - 25 \Delta$ (Table III).

Four subjects in experiment II did not follow this trend and their data is shown separately in figure 4a (solid gray lines). These four subjects were re-examined at the UC Berkeley Optometry clinic for subtle binocular vision anomalies that went un-noticed 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 reexamine all the other subjects who took part in experiment II. Number subjects were not available for reexamination due to either re-location or due to 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 either based on race (Asian or Caucasian) of the subject (p-value: >0.05) (data not shown) or based on their gender (p-value: >0.05) (data not shown).

4. Control experiments

Two different control experiments were performed. As does convergence⁴³, the vertical vergence system exhibits hysteresis following sustained periods of disparity stimulation^{33, 44,45}. For instance, Ogle and Prangen³³ observed that vertical vergence could respond to vertical disparities as large as 6Δ within $3 - 10$ min. 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 al⁴⁵ proposed that the reduction in vertical deviation in patients with superior oblique palsy could be related the adaptable component of vertical vergence. Since in both experiments I and II, the vertical vergence stimulus was incremented only after subject reported fusion of the targets, it raises the possibility that the imposed vertical vergence response could be extended by a short-term

'adaptable' component of vertical vergence. To test this possibility, experiment I was repeated on 3 subjects with the modification that the vertical disparities were incremented in steps of 0.05Δ once every 6 secs. 6 secs 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 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 al⁴. For each subject, the slope and y-intercept of linear regression equation obtained in the control experiment was compared with the respective slope and y-intercept obtained in experiment I for statistically significant differences⁴². The difference in slopes and y-intercepts were statistically insignificant (p-value: >0.5) for all three subjects (data not shown). These results suggest that the 'adaptable' component of vertical vergence is unlikely to influence the VFA's 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 & II. In both experiments, vertical disparities were produced by symmetrically and simultaneously displacing the right-eye image upwards and the left-eye image downwards (right-hyper disparity). We tested if VFA depended on the sign of the vertical disparity in three subjects by comparing responses to a right-hyper stimulation paradigm, and a left-hyper stimulation paradigm (displacing the left-eye image upwards and the right-eye image downwards). 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-hyper stimulation paradigms. For each subject, the slopes and y-intercepts of linear regression equations obtained in the left-hyper and the right-hyper paradigm were compared for statistically significant differences⁴². The difference in slopes and y-intercepts were statistically insignificant (p-value: >0.5) for all three subjects (data not shown). Hence, for those 3 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 Prangen³³ when they measured the VFA's to right- and left-hyper disparity paradigms using the vertical fixation-disparity technique.

5. Discussion

The main aim of this experiment was to develop a quantitative description of coupling between VFA and convergence. We measured the VFA during several (maximum of nine) convergence angles. The results of experiments I and II show that the VFA increases with convergence in 52 of 56 subjects tested (Figures 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, that VFA increased linearly with convergence (Figures 3b, 4b & 5b). The group-linear regression equations obtained from experiments I and II were $y = 0.10x + 1.62$ (Figure 3b) and $y = 0.09x + 2.05$ (Figure 4b) respectively. The linear regression equation obtained by pooling the data of experiment I and II was $y = 0.10x + 1.82$ (Figure 5b). The coefficients of the linear regression equation were very robust to the inter-subject variability as evidenced the narrow $\pm 99\%$ confidence intervals (Figure 5b). Furthermore, the linear regression equation did not vary significantly with the experimental condition (experiment I, II and the two control experiments), race or gender.

All components of the oculo-motor system (e.g. horizontal disparity vergence⁴⁶ and ocular accommodation⁴⁷) are characterized by the presence of significant intra- and inter-subject variability. Variability could either have a biological origin or it could be introduced by external factors related to measurement. While the exact source of variability was not systematically investigated in our experiment, the data showed that the VFA exhibits a small amount of inter-subject variability (Figure 5c). This inter-individual variability when expressed in terms of the

$\pm 99\%$ confidence intervals (Figure 5c, Table III) indicates that, for a given convergence angle (within $0 - 25 \Delta$), the VFA's of our subjects are likely to fall within the range 99% of times. For instance, amongst the 52 subjects tested, the magnitude of inter-subject variability (estimated from the 99% confidence interval of the mean) was approximately $1/5^{\text{th}}$, $1/11^{\text{th}}$ and $1/10^{\text{th}}$ of the mean VFA's at 0 , 14 and 25Δ of convergence respectively (Figure 5c). The inter-subject variability also remained fairly constant ($0.31 - 0.50 \Delta$) across a large range of convergence angles ($0 - 25 \Delta$) (Figure 5c, Table III). As noted earlier, although the inter-subject variability did reduce the correlation of determinant (r^2) between the VFA and convergence (Figure 3b, 4b, 5b), its influence on the robustness of the group-average linear regression equations was minimal as evidenced by the narrow $\pm 99\%$ confidence intervals (Figure 3b, 4b, 5b). Furthermore, the correlation of determinant of the individual linear regression equations were 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 inter-subject variability.

The population distributions of vertical phorias at far (approx. 20 feet) and near (approx. 13 inches) are very similar to each other^{48,49}, with the mean vertical phoria close to 0Δ at both viewing distances^{48,50,51}. The similarity in distributions is retained even when the distributions are only composed of patients with 'clinically significant' ($> 0.5 \Delta$) distance and near vertical phorias⁴⁹. 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 to 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 al⁴⁵ observed that in a group of 84 patients with superior oblique palsy, 23 of them had smaller vertical deviations at a near viewing distance than at a far viewing distance. In another study, Gräf et al⁵² found that in a group of 19 patients with superior oblique palsy, the amplitude of vertical deviation increased with viewing distance in 4 patients. The remaining patients (61 patients in Ohtsuki et al's study and 15 patients in Graf et al's study) 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 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 fusion⁵³. 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 non-homogeneity in the pathophysiology of superior oblique palsy observed in these patients.

Hara et al showed that the increase in VFA with convergence is brought about by an increase in the motor component of vertical vergence⁴. The exact reason for the increase in the motor component of VFA with convergence remains unanswered. While the experiments performed here do not provide an answer, they exclude three plausible explanations that are worth considering. First, it has been shown by a number of 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, since both experiment 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^{33,39,45}. Larger VFA's have been observed previously following vertical prism adaptation by Ogle and Prangen³³. 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 secs 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-value: >0.05). The results of both control experiment II and main experiment I also compare well with the results obtained by Hara et al who estimated the VFA by incrementing the vertical vergence stimulus once every 6 secs. These results suggest that the adaptable component of the vertical vergence system could only have a minor role to play 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 viewing², it is plausible that the increase in VFA at near viewing is related to accommodation or to the 'sense of proximity' of the fusion targets¹⁵. 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 cms 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 cms in front of the subject. Although weak and ineffective in the presence of other visual and non-visual cues⁵⁴⁻⁵⁶, 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 vergence³⁹. 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 pre-programmed (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 pre-programmed cross-link whose gain is analogous to the cross-link gains between accommodation and convergence (AC/A^{57,58} and CA/C^{59,60} 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}. This study found that, in a group of 52 individuals, the VFA increases with convergence angle and this increase could be described by a linear regression equation ($VFA = 0.10 * \text{convergence angle} + 1.82$) (Figure 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 (Figure 5b, Table III). This suggests that if the VFA norm is employed 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 for binocular viewing distances farther than 67 cm. Furthermore, the VFA norm would be rendered ineffective as a diagnostic metric when the VFA change between distance-viewing (approximately 6 m) and near-viewing (approximately 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 inter-individual variability of VFA's noted in our experiment shows that a range of VFA's can be expected at any given viewing distance (Figure 5b, c). 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 $\pm 99\%$ confidence intervals shown in Figure 5c and Table III for a range of convergence angles (within 0 – 25 Δ).

5. 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. Our study measured the VFA at nine different convergence angles, and described the relationship between VFA and convergence response using a simple linear regression equation that was very robust to the inter-subject variability. It did not show any significant changes with experimental conditions, race or sex. The linear regression equation developed here 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).

Acknowledgements

The authors would like to thank all the subjects who took part in the experiment. They would also like to acknowledge the travel grant provided to Sivaramakrishnan to attend the Singapore Eye Research Institute (SERI) – Association for Research in Vision and Ophthalmology (ARVO) conference in Singapore. Financial support for this research was provided by a NIH grant (EY03532) to Clifton M. Schor.

References

- Howard, IP.; Rogers, BJ. Binocular vision and stereopsis. Oxford: Oxford University; 1998.
- Schor CM, Maxwell JS, Stevenson SB. Isovergence surfaces: the conjugacy of vertical eye movements in tertiary positions of gaze. *Ophthalmic Physiol Opt* 1994;14:279–286. [PubMed: 7970742]
- Berens C, Losey RR, Hardy LH. Routine examination of the ocular muscles and nonoperative treatment. *Am J Ophthalmol* 1927;10:910–918.
- Hara N, Steffen H, Roberts DC, Zee DS. Effect of horizontal vergence on the motor and sensory components of vertical fusion. *Invest Ophthalmol Vis Sci* 1998;39:2268–2276. [PubMed: 9804135]
- Parks, M. Vergences. In: Tasman, W.; Jaeger, EA., editors. *Duane's Clinical Ophthalmology*. Philadelphia: Lippincott Williams and Wilkins; 2005.
- Sharma K, Abdul-Rahim AS. Vertical fusion amplitude in normal adults. *Am J Ophthalmol* 1992;114:636–637. [PubMed: 1443031]
- Takao S. Vertical fusion amplitude. *J Jpn Ophthalmol Soc* 1936;40:245–251.
- Stevenson SB, Lott LA, Yang J. The influence of subject instruction on horizontal and vertical vergence tracking. *Vision Res* 1997;37:2891–2898. [PubMed: 9415368]
- Perlmutter AL, Kertesz AE. Measurement of human vertical fusional response. *Vision Res* 1978;18:219–223. [PubMed: 664294]
- Ygge, J. Vertical vergence - normal function and plasticity. In: Franzen, O.; Richter, H.; Stark, L., editors. *Accommodation and vergence mechanisms*. Switzerland: Birkhauser Verlag Basel; 2000.
- Duwaer AL. Nonmotor component of fusional response to vertical disparity: a second look using an afterimage method. *J Opt Soc Am* 1982;72:871–877. [PubMed: 7108645]

12. Fender D, Julesz B. Extension of Panum's fusional area in binocularly stabilized vision. *J Opt Soc Am* 1967;57:819–830. [PubMed: 6038008]
13. Kertesz AE, Perlmutter AL. Vertical fusional response to asymmetric disparities. *IEEE Trans Biomed Eng* 1983;30:246–250. [PubMed: 6862507]
14. Perlmutter AL, Kertesz AE. Human vertical fusional response under open and closed loop stimulation to predictable and unpredictable disparity presentations. *IEEE Trans Biomed Eng* 1982;29:57–60. [PubMed: 7076271]
15. Ygge J, Zee DS. Control of vertical eye alignment in three-dimensional space. *Vision Res* 1995;35:3169–3181. [PubMed: 8533351]
16. Houtman WA, Roze JH, Scheper W. Vertical motor fusion. *Doc Ophthalmol* 1977;44:179–185. [PubMed: 923409]
17. Howard IP, Allison RS, Zacher JE. The dynamics of vertical vergence. *Exp Brain Res* 1997;116:153–159. [PubMed: 9305824]
18. Borish, IM. Borish's Clinical Refraction. Philadelphia: W. B. Saunders; 1998.
19. Grosvenor, TP. Primary care optometry. Boston: Butterworth-Heinemann; 2002.
20. Ellerbrock VJ. Experimental investigation of vertical fusional movements. *Am J Optom Arch Am Acad Optom* 1949;26:327–337. [PubMed: 18136744]
21. Allison RS, Howard IP, Fang X. Depth selectivity of vertical fusional mechanisms. *Vision Res* 2000;40:2985–2998. [PubMed: 11000396]
22. Howard IP, Fang X, Allison RS, Zacher JE. Effects of stimulus size and eccentricity on horizontal and vertical vergence. *Exp Brain Res* 2000;130:124–132. [PubMed: 10672465]
23. Kertesz AE. Effect of stimulus size on fusion and vergence. *J Opt Soc Am* 1981;71:289–293. [PubMed: 7218073]
24. Luu CD, Abel L. The plasticity of vertical motor and sensory fusion in normal subjects. *Strabismus* 2003;11:109–118. [PubMed: 12854018]
25. Robertson KM, Kuhn L. Effect of visual training on the vertical vergence amplitude. *Am J Optom Physiol Opt* 1985;62:659–668. [PubMed: 4073199]
26. Rutstein RP. Vertical vergence adaptation for normal and hyperphoric patients. *Optom Vis Sci* 1992;69:289–293. [PubMed: 1565429]
27. Rutstein RP, Daum KM, Cho M, Eskridge JB. Horizontal and vertical vergence training and its effect on vergences, fixation disparity curves, and prism adaptation: II. Vertical data. *Am J Optom Physiol Opt* 1988;65:8–13. [PubMed: 3348354]
28. Burian, H.; von Noorden, GK. Binocular vision and ocular motility. St. Louis: C. V. Mosby; 1985.
29. Mottier ME, Mets MB. Vertical fusional vergences in patients with superior oblique muscle palsies. *Am Orthopt J* 1990;40:88–93.
30. Rutstein RP, Corliss DA. The relationship between duration of superior oblique palsy and vertical fusional vergence, cyclodeviation, and diplopia. *J Am Optom Assoc* 1995;66:442–448. [PubMed: 7560733]
31. Grafe A. Ueber die fusionsbewegungen der augen beim prismaversuche. *Graefes Arch Clin Exp Ophthalmol* 1891;37:243–257.
32. Boman DK, Kertesz AE. Interaction between horizontal and vertical fusional responses. *Percept Psychophys* 1983;33:565–570. [PubMed: 6622192]
33. Ogle KN, Prangen AD. Observations on vertical divergences and hyperphorias. *AMA Arch Ophthalmol* 1953;49:313–334. [PubMed: 13030008]
34. Ellerbrock VJ. The effect of aniseikonia on the amplitude of vertical divergence. *Am J Optom Arch Am Acad Optom* 1952;29:403–415. [PubMed: 14952553]
35. Morgan MW. Analysis of clinical data. *Am J Optom Arch Am Acad Optom* 1944;21:477–491.
36. Brainard DH. The Psychophysics Toolbox. *Spat Vis* 1997;10:433–436. [PubMed: 9176952]
37. Pelli DG. The VideoToolbox software for visual psychophysics: transforming numbers into movies. *Spat Vis* 1997;10:437–442. [PubMed: 9176953]
38. Schor CM, McCandless JW. An adaptable association between vertical and horizontal vergence. *Vision Res* 1995;35:3519–3527. [PubMed: 8560816]

39. Schor CM, McCandless JW. Distance cues for vertical vergence adaptation. *Optom Vis Sci* 1995;72:478–486. [PubMed: 8539011]
40. McArdale BH. The structural relationship: regression in biology. *Canadian Journal of Zoology* 1988;66:2329–2339.
41. Devore, J.; Peck, R. Simple linear regression and correlation: inferential methods. In: Devore, J.; Peck, R., editors. *Statistics -The Exploration and Analysis of Data*. 2. Belmont: Wadsworth; 1993. -731.p. 802
42. Kleinbaum, DG.; Kupper, LL.; Muller, KE.; Nizam, A. Dummy variables in regression. In: Kleinbaum, DG.; Kupper, LL.; Muller, KE.; Nizam, A., editors. *Applied regression analysis and multivariable methods*. 3. Pacific Grove: Duxbury Press; 1998. p. 317-360.
43. Sethi B. Vergence adaptation: a review. *Doc Ophthalmol* 1986;63:247–263. [PubMed: 3536367]
44. Ellerbrock VJ, Fry GA. The after-effect induced by vertical divergence. *Am J Optom Arch Am Acad Optom* 1941;450–454.
45. Ohtsuki H, Hasebe S, Furuse T, Nonaka F, et al. Contribution of vergence adaptation to difference in vertical deviation between distance and near viewing in patients with superior oblique palsy. *Am J Ophthalmol* 2002;134:252–260. [PubMed: 12140032]
46. Semmlow JL, Yuan W. Components of disparity vergence eye movements: application of independent component analysis. *IEEE Trans Biomed Eng* 2002;49:805–811. [PubMed: 12148819]
47. Schaeffel F, Wilhelm H, Zrenner E. Inter-individual variability in the dynamics of natural accommodation in humans: relation to age and refractive errors. *J Physiol* 1993;461:301–320. [PubMed: 8350267]
48. Letourneau JE, Giroux R. Nongaussian distribution curve of heterophorias among children. *Optom Vis Sci* 1991;68:132–137. [PubMed: 2027652]
49. Scobee R, Bennet E. Hyperphoria - A statistical study. *Arch Ophthalmol* 1950;43:458–465.
50. Casillas E, Rosenfield M. Comparison of subjective heterophoria testing with a phoropter and trial frame. *Optom Vis Sci* 2006;83:237–241. [PubMed: 16614580]
51. Jimenez R, Perez MA, Garcia JA, Gonzalez MD. Statistical normal values of visual parameters that characterize binocular function in children. *Ophthalmic Physiol Opt* 2004;24:528–542. [PubMed: 15491481]
52. Graf MH, Rost D, Becker R. Influence of viewing distance on vertical strabismus. *Graefes Arch Clin Exp Ophthalmol* 2004;42:571–575. [PubMed: 15029503]
53. Maxwell JS, Schor CM. The coordination of binocular eye movements: Vertical and torsional alignment. *Vision Res*. 2006
54. Keller EL, Robinson DA. Absence of a stretch reflex in extraocular muscles of the monkey. *J Neurophysiol* 1971;34:908–919. [PubMed: 4255469]
55. Skavenski AA, Haddad G, Steinman RM. The extraretinal signal for the visual perception of direction. *Percept Psychophys* 1972;11:287–290.
56. Steinbach MJ. Proprioceptive knowledge of eye position. *Vision Res* 1987;27:1737–1744. [PubMed: 3328405]
57. Alpern M, Kincaid WM, Lubeck MJ. Vergence and accommodation. III. Proposed definitions of the AC/A ratios. *Am J Ophthalmol* 1959;48:141–148. [PubMed: 13670274]
58. Fry GA. An experimental analysis of the accommodation-convergence relation. *Am J Optom Arch Am Acad Optom* 1937;14:402–414.
59. Balsam MH, Fry GA. Convergence accommodation. *Am J Optom Arch Am Acad Optom* 1959;36:567–575. [PubMed: 13796321]
60. Kent PR. Convergence accommodation. *Am J Optom Arch Am Acad Optom* 1958;35:393–406. [PubMed: 13571367]

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 figures a & b). The convergence stimulus was larger in figure b than in figure 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 figures c & d). The convergence stimulus was larger in figure d than in figure c. The red concentric circle and red filter are shown in black while the green concentric circle and green filter are shown in gray. These figures show the state of two eyes prior to fusing the convergence stimulus. For the sake of clarity, the vertical vergence stimulus was 0Δ in these figures.

Vertical fusion stimulus = $\alpha + \beta$

Convergence angle = γ

F_L : Left eye Fovea F_R : Right eye Fovea

SR_L : Left eye Superior retina IR_R : Right eye inferior retina

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 while the green concentric circle and green filter are shown in gray. In the experiment, vertical disparities were generated by vertical displacing the red-green concentric circles in steps of 0.05Δ .

Figure 3.

VFA plotted as a function of the convergence stimuli for individual subjects in experiment I. a) Raw data of 30 individual 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 $\pm 99\%$ 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 individual subjects who showed an increase in VFA with convergence stimuli (dashed gray lines) along with the raw data of the 4 outliers (solid black lines). b) Linear regression equations fit to the raw data of these 22 individual subjects (dashed gray lines) along with the group-linear regression equation fit (thick black line) and $\pm 99\%$ confidence intervals (black dashed curves). The results of experiments I and II were both qualitatively and quantitatively similar to each other (compare figures 3 and 4).

Figure 5.

Pooled data from experiments I and II. a) Raw data of 52 individual subjects who showed an increase in VFA with convergence. Solid red and blue lines show data from experiment I and II respectively. 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 $\pm 99\%$ confidence intervals (black dashed curves). c) The mean (black line) and $\pm 99\%$ confidence interval of the mean (dashed gray lines) of the VFA's at each 1 Δ convergence bin. The mean and $\pm 99\%$ confidence interval was obtained by averaging the individual linear regression equation estimated VFA obtained from 52 subjects.

Table I

The individual orthogonal-linear regression equation fit to the data of VFA plotted as a function of convergence stimulus obtained from experiment I. The percentage variance described by the linear regression equation is given by the individual r^2 values in column 3. The p-value describing the statistical significance of the slope of the individual linear regression equations is given in column 4. Small p-values indicate that in majority of the subjects the slope of the linear regression equation was statistically significantly different from zero.

Subjects	Linear regression equation	R ² values	P-value
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	

Table II

The individual orthogonal-linear regression equation fit to the data of VFA plotted as a function of convergence stimulus obtained from experiment II. The data of 4 outliers whose data could not be fit with linear regression equations are not shown in this table. The percentage variance described by the linear regression equation is given by the individual r^2 values in column 3. The p-value describing the statistical significance of the slope of the individual linear regression equations is given in column 4. Small p-values indicate that in majority of the subjects the slope of the linear regression equation was statistically significantly different from zero.

Subjects	Linear regression equation	R ² values	P-value
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	

Table III

The mean and $\pm 99\%$ confidence interval of the mean of the VFA's at each 1 Δ convergence bin. The mean and $\pm 99\%$ confidence interval was obtained by averaging the individual linear regression equation estimated VFA obtained from 52 subjects. This provides a quantitative estimate of the inter-subject variability of VFA at different convergence bins.

Convergence stimulus (Δ)	Mean VFA (Δ)	$\pm 99\%$ 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