

# COMPONENTS OF CLINICAL NEAR VERGENCE TESTING

First Annual Invited Paper

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## ABSTRACT

*Vergence refers to the disjunctive movement of the eyes used to track targets moving in depth. In this invited paper, the sensory, motor, and perceptual aspects of clinical near vergence testing are described and discussed in detail, with introduction of concepts developed in bioengineering. In addition, new tests are described and suggested for use by the functional optometrist.*

## KEY WORDS

*vergence, eye movements, accommodation, clinical optometric vergence testing*



During the early development of optometry in the 1920s and 1930s, two different approaches to clinical near vision testing and analysis evolved. The first, called graphical analysis, was gradually developed by such notables as Percival, Sheard, Fry and Hofstetter and became embraced by academic optometry.<sup>1-3</sup> Essentially, a variety of near vision findings were plotted on a special graph, and a zone of comfort was defined. If the patient normally operated within this zone, all was presumed to be fine; if not, then lenses, prisms, and/or vision therapy were prescribed to obtain a normal operating status within this zone. In contrast, the second approach, termed functional vision or analytical (OEP) analysis, was gradually developed by such eminent clinicians as Skeffington, Alexander, and Hendrickson and became embraced by many practicing optometrists as a more exciting and creative alternative to graphical analysis.<sup>4-6</sup> While it primarily relied on a similar set of near vision findings, the analytical analysis developed a unique set of rules and equations to guide the practitioner to the optimal intervention. Further, inherent in the OEP methodology was speculation on the etiology and developmental stages of the anomalous visual condition as well as possible preventive measures.

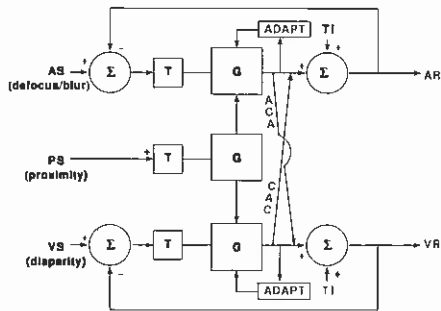
As optometrists, we perform a wide array of near vergence tests to determine a patient's oculomotor abilities for diagnostic, prognostic and therapeutic purposes. While there are numerous detailed clinic manuals and textbooks explicitly

specifying the step-by-step procedures to accomplish such measurements, the underlying physiology and physiological optics principles are frequently minimal or even absent. Thus, it is most fitting in this first annual *Journal of Behavioral Optometry's* Invited Paper to review and expand upon, in detail, the sensory and motor physiology and physiological optics of clinical near vergence testing and relate it to current concepts in binocular vision (also see Howell's recent review).<sup>7</sup> This should help students to understand more precisely the complexity, and to introduce practitioners to concepts and terms from bioengineering theory, that are being used to characterize and investigate this finely coordinated oculomotor system. I trust the present paper will also serve to provide some interesting, and perhaps personal, insights into these routine but complex oculomotor behavioral responses requested of our patients each day.

## DEFINITIONS AND A MODEL OF THE VERGENCE SYSTEM

Vergence refers to the disjunctive movement of the eyes which is executed to track a target moving in three-dimensional space.<sup>8</sup> It can be horizontal, vertical or cyclorotary in nature, although the clinical emphasis is placed on its horizontal range and dynamic responsivity. The vergence response consists of two parts. The sensory component is involved in sensing and processing the disparity and blur inputs. The motor component receives the coded disparity and blur information, and subsequently generates an

**SIMPLIFIED MODEL OF THE VERGENCE AND ACCOMMODATION SYSTEMS**



**Figure 1.** Steady-state model of the vergence system. (Hung, Ciuffreda, and Rosenfield, unpublished results). Symbols: AS = accommodative stimulus, VS = disparity stimulus, PS = proximal stimulus, AR = accommodative response, VR = vergence response,  $\Sigma$  = summing junction for various inputs, T = threshold detector, G = system gain, ADAPT = adaptive component, ACA = accommodative convergence to accommodation (crosslink gain), CAC = convergence accommodation to convergence (crosslink gain), and TI = tonic input.

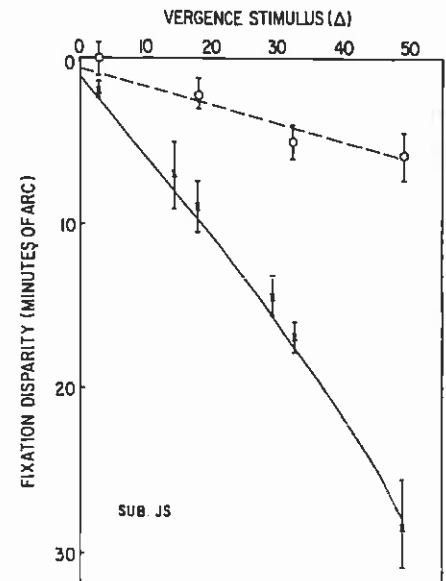
appropriate neuromotor command to verge the eyes so that the defocused and disparate retinal images again fall within Panum's fusional areas in a focused manner. This motor command is also available to the perceptual system to provide it with information regarding apparent target distance.<sup>9,10</sup> Furthermore, perceptually-driven target proximity may influence the overall motor response.

The Maddox components of the vergence system,<sup>11</sup> and their interactions,<sup>8</sup> can perhaps best be described within the context of a model (Figure 1). The first component is *accommodative vergence* with its blur-driven input.<sup>12</sup> The accommodative system itself first receives a defocused retinal image. If the amount of defocus exceeds a blur threshold, i.e., the depth of focus or tolerance for accommodative error, resulting in the perception of blur, this information is then transmitted to the accommodative gain element (a multiplier which effectively determines the system response magnitude for that stimulus change) where the initial accommodative neural control signal is generated. This signal then proceeds to the neuromotor system (midbrain) and eventually stimulates the accommodative apparatus, i.e., lens-ciliary body complex, to change lens power appropriately to obtain an in-focus retinal image. Concurrently, this initial signal is crossed over to the vergence system, and it can be thought of as producing the associated change in

accommodative vergence involved in measurement of the ACA ratio. The second component is *disparity (or fusional) vergence* with retinal disparity as its primary input.<sup>13-15</sup> Analogous to the accommodative system, if the disparity magnitude exceeds its threshold value, i.e., Panum's fusional area or tolerance for vergence error, then this information is transmitted to the vergence gain element (a multiplier which effectively determines the system response magnitude for that stimulus change) where the initial vergence neural control signal is generated. This signal then proceeds to the neuromotor system (midbrain) and eventually stimulates the extraocular muscles to change the vergence angle to obtain a single, fused image. Concurrently, the initial signal is also crossed over to the accommodative system, and it can be thought of as producing the associated change in vergence accommodation involved in measurement of the CAC ratio. The third is *proximal vergence* with its input being the perception of apparent nearness of the object of regard.<sup>16</sup> If the change in apparent nearness of a target exceeds some (yet unknown) proximity threshold, the perceptually-related information proceeds to stimulate both the accommodative system and the disparity vergence system.<sup>17,18</sup> The final component is *tonic vergence* which is driven by the baseline neural innervation.<sup>19</sup> Under normal viewing conditions, it probably exerts little influence on the overall vergence response.<sup>20</sup> When the other three vergence components are rendered ineffective, tonic vergence can be assessed.<sup>21</sup> These four vergence components interact nonlinearly to produce a single and clear binocular percept. In addition, the adaptive ability (i.e., gradual take-over by the sustained element of the transient element of the disparity vergence system as found, for example, either during habitual sustained fixation or prism adaptation; see ADAPT element in Figure 1) of these vergence components probably plays a role in the maintenance of comfortable vision during sustained nearpoint activities.<sup>22-24</sup>

**ISOLATED DISPARITY (OR FUSIONAL) VERGENCE**

Under standard clinical test conditions, the disparity (or fusional) vergence



**Figure 2.** Fixation disparity as a function of vergence stimulus demand with accommodation either open-(o) or close-(x) looped. Absence of a blur-driven accommodative component during binocular fixation with accommodation open-looped results in substantial reduction in fixation disparity, especially as the vergence demand is increased. Plotted is  $\bar{x} \pm 1$  S.D. Reprinted with permission of the publisher, from Semmlow and Hung, 1979.

response is not probed in isolation from accommodation and its synkinetically-driven accommodative vergence. However, this has been performed experimentally, and the findings warrant brief discussion as they add to our general understanding of vergence and accommodative interactions and appear to have clinical utility.

With regards to the steady-state (or final sustained) response, Semmlow and Hung<sup>25</sup> generated Ogle-type forced-vergence fixation disparity curves in visually-normal individuals. Accommodation was either in the normal "closed-loop" mode, in which blur feedback was available, or in the "open-loop" mode (via pinholes), in which blur feedback was not available so that the disparity vergence system alone responded. The results are presented in Figure 2 for the base-out region. Clearly, fixation disparity was considerably larger when disparity vergence, accommodation and accommodative vergence interacted in the normal closed-loop mode. In fact accommodative interactions accounted for up to 50% of the measured fixation disparity found under normal viewing conditions. From these results, one could speculate that in a patient with abnormal accommodation,

## ISOLATED TONIC VERGENCE

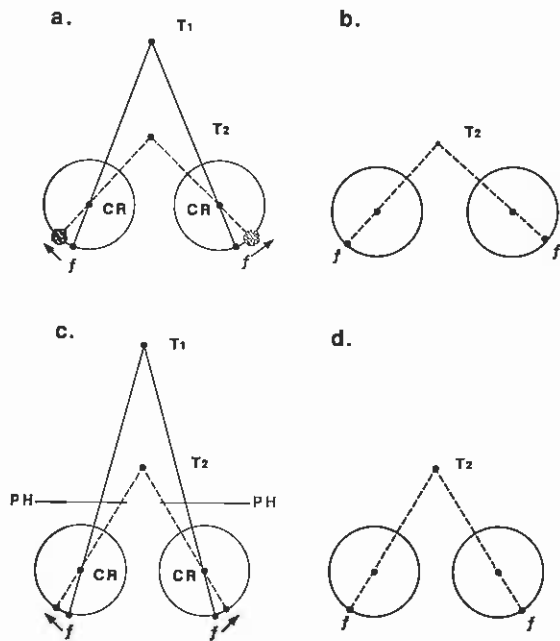
As discussed earlier, in the absence of disparity, blur and proximal stimuli (such as in total darkness), one is left with the isolated tonic vergence input. It probably plays only a minor role (response bias effect) in the overall vergence response, especially at near under standard viewing conditions in visually-normal individuals.<sup>20</sup> However, a brief discussion of tonic vergence is appropriate as it adds to our general understanding of vergence and accommodation interactions and may indeed have clinical utility.

In visually-normal adults, tonic vergence is typically 2 prism diopters more convergent than the distant phoria as measured by the Maddox rod technique.<sup>27</sup> Thus, tonic vergence can be estimated in this manner and has proven to be repeatable over time due to its stable nature.<sup>21</sup> However, it can also be measured directly and quite simply by incorporating pinhole apertures before the eyes during distance von Graefe phoria testing. With this arrangement, the disparity vergence and accommodation systems are open-loop, and the proximal input is absent (>3m);<sup>18</sup> this isolates the tonic vergence component. If one takes this measurement immediately before and after a period of sustained near vision, the obtained value includes tonic vergence together with the disparity vergence adaptive contribution. This information may be of diagnostic importance.<sup>22-24</sup> Furthermore, the possible role of abnormal tonic vergence drive in strabismus (especially esotropia at distance) has yet to be determined.

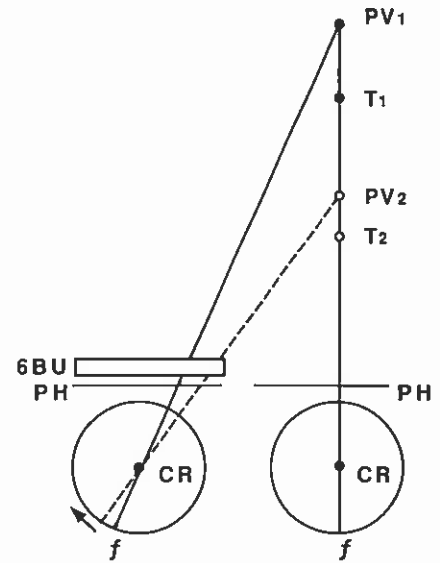
the accommodative interactive effects might even have a greater adverse impact on the final vergence error (i.e., fixation disparity). This supports the notion of many behavioral optometrists that accommodative abnormalities contribute to vergence dysfunction. This could be tested directly by obtaining a patient's forced-vergence curve with and without pinhole apertures (<1mm) in a trial frame. Such testing would allow the practitioner to "tease out" the contribution of accommodation from that of disparity in the overall vergence system response and therefore tailor the treatment more specifically toward one system rather than the other.

In contrast, under test conditions where the subject is now asked to verge upon targets located at different distances (Figure 3), the open- and closed-loop dynamic (i.e., transient) aspects of the vergence responses were almost identical.<sup>26</sup> Whether this would be true in patients with accommodative dysfunction has yet to be investigated. Clinically, one could attach a variable interpupillary pinhole system to prism flippers to probe this area. As described in the previous paragraph, such testing "teases out" the system's component contribution and may provide important information for a more directed treatment plan.

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**Figure 3.** Vergence tracking with (a,b) and without (c,d) a blur-driven contribution. Symbols:  $T_1$  = far target,  $T_2$  = near target, PH = pinhole, CR = center of rotation of eye, and  $f$  = fovea.



**Figure 4.** Clinical measurement of proximal vergence. Symbols:  $T_1$  = target position one,  $T_2$  = target position two,  $PV_1$  = proximal vergence in response to  $T_1$ ,  $PV_2$  = proximal vergence in response to  $T_2$ , PH = pinhole, BU = base-up prism, CR = center of rotation of eye, and  $f$  = fovea.

gests that its contribution may be substantial. Research shows a gain of 0.5, i.e., a 0.5 meter angle response per meter angle of stimulus change, under open-loop viewing conditions.<sup>18</sup> This may be the case for individuals having either normal or abnormal binocular vision.<sup>16</sup>

Proximal vergence can be measured directly and quite simply in the clinic by incorporating pinhole apertures before the eyes (to eliminate accommodative vergence) and measuring the heterophoria using the von Graefe prism dissociation technique (to eliminate disparity vergence) (Figure 4). Changes in the proximal stimulus can be introduced by measuring this "pinhole phoria" to targets located at different viewing distances, e.g., 1.0, 0.5, 0.33, and 0.25m. The change in "phoria" will provide an estimate of proximal vergence. Care must be taken to ensure that the patient is fully aware of the actual target location to provide the optimal stimulus to proximal vergence. This can be accomplished by having the patient view the targets under closed-loop viewing conditions before recording the measurements, or alternatively by having them hold each target during the measurements.

## VERGENCE PRIMARY AND ACCOMMODATION SECONDARY

### Near Point of Convergence

The nearpoint of convergence represents the point of intersection of the lines of sight when the eyes are in a position of maximum convergence. This nearest point of bifixation is normally ap-

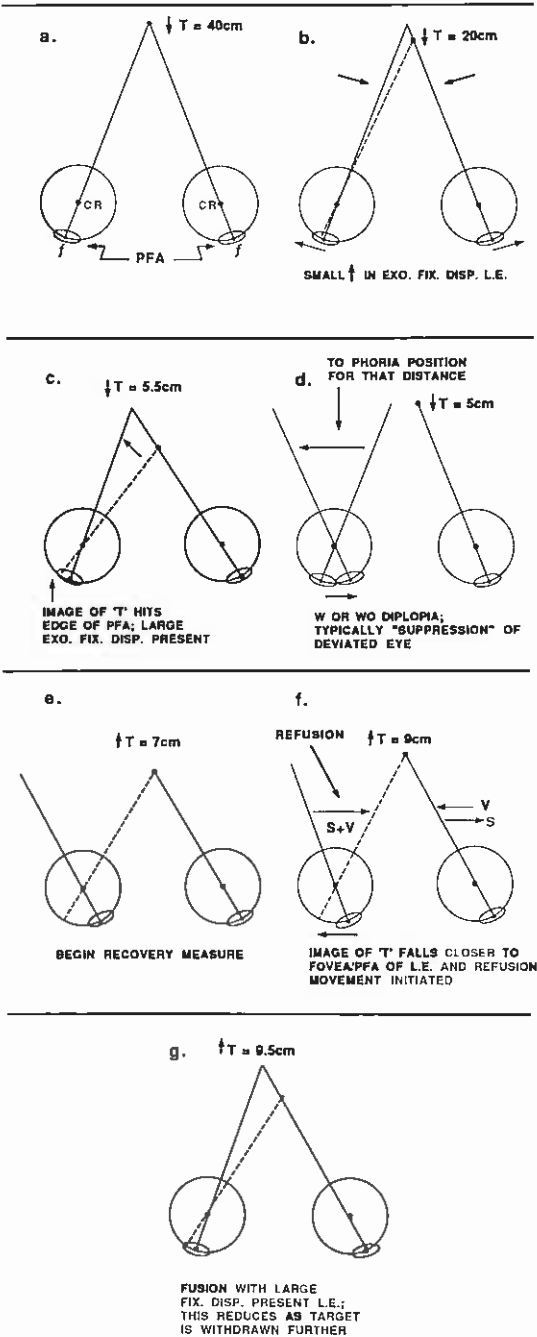
proximately 5 cm.<sup>28</sup> In contrast, the far point of convergence represents the point of intersection of the lines of sight when the eyes are in a position of minimum convergence. This farthest point of bifixation is within (plus or minus) a few minutes of arc of infinity. Thus, the amplitude of convergence is the difference in convergence power (generally in meter angles [MA] reciprocal of target distance) between the near- and far-points of convergence, typically equalling approximately 20 meter angles, 120 prism diopters, or 70 degrees. Since the convergence far-point is, for all practical purposes, at infinity, the amplitude of convergence essentially equals the convergence nearpoint.

The various phases in the clinical measurement of the nearpoint of convergence are presented in Figure 5. Let us assume that the clinician starts testing at 40 cm using a small, detailed target (to provide an effective stimulus to the accommodative and fusional vergence systems) which impinges precisely upon the center of Panum's fusional area at the fovea in each eye (Figure 5a). It should be kept in mind that since convergence, like accommodation, is spatially non-linear (i.e., the reciprocal of target distance), one must move the target inward progressively more slowly to maintain a constant rate of stimulation in terms of meter angles/second. As the target approaches the patient, the overall convergence angle of the eye increases, and a small exo fixation disparity probably occurs, which, for simplicity, can be assigned entirely to the left eye (Figure 5b). As the target advances further (5.5 cm) (Figure 5c) and is approaching the convergence nearpoint (5 cm), its retinal image strikes the templeward edge of Panum's fusional area in the left eye, so that a relatively large (5-10 min arc) vergence error or fixation disparity is present. With an additional 0.5 cm of target movement, the nearpoint of convergence is reached (Figure 5d). Fusion would therefore no longer be possible (objective nearpoint), and the left eye would slowly (3-5 or more sec) shift to the steady-state

phoria position for that distance; this would probably produce a large (approximately 120 prism diopters, assuming a 6 cm inter-pupillary distance) exo deviation as exophoria at near is the norm.<sup>29</sup> Diplopia might also be reported at this point (subjective nearpoint) by the patient, although "suppression" (perhaps really "inattention" to the markedly peripheral and defocused image) is also possible. Once the objective and subjective nearpoints are determined, the subjective and objective recovery values should be ascertained. Now, as the target is slowly moved away from the patient, its retinal image in the left eye gradually shifts toward the fovea (Figure 5e). At a certain instant, but still well outside the edge of the foveal Panum's region, a refusion movement would be initiated (9 cm) (Figure 5f). At 9.5 cm, fusion is attained, but with presence of a large exo fixation disparity in the left eye (Figure 5g). This magnitude of fixation disparity would gradually reduce with further withdrawal of the nearpoint target.

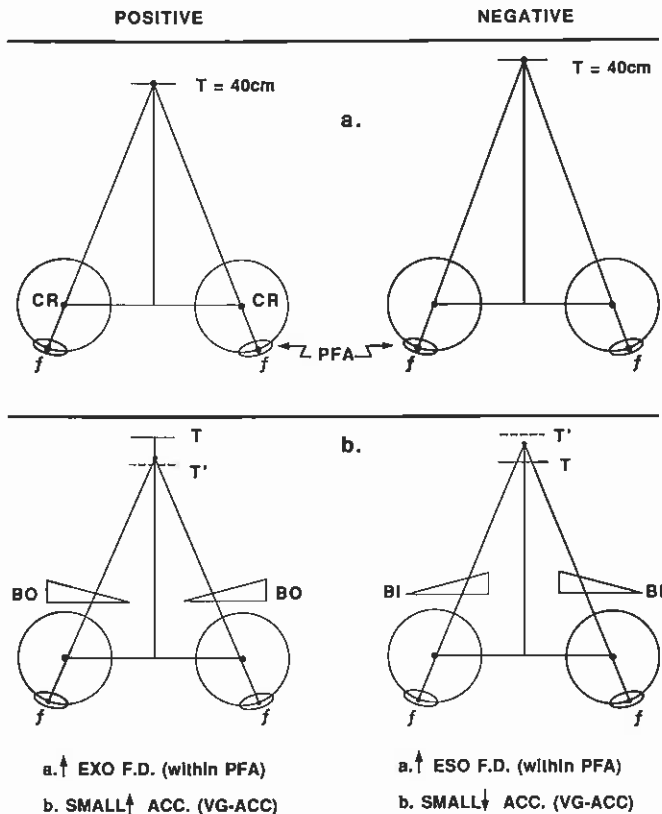
What components of vergence are stimulated during this test? Certainly symmetric disparity vergence is stimulated, as the clinician moves the target along the midline while the patient attempts to maintain a fused, single image (Figure 5a). However, at the point of refusion during the recovery measurement, the motor response is that of asymmetric disparity vergence, since the disparity error is not distributed symmetrically between the two eyes (Figure 5f). Accommodative vergence is also activated, as target movement produces retinal defocus and subsequent blur, which is compensated by an appropriate change in accommodation; however, the accommodative vergence drive will reduce markedly during the measurement itself once the accommodative amplitude has been exceeded. Thirdly, since physical target movement toward and away from the patient at near is evident, proximal vergence is stimulated. And, lastly, one might think that tonic vergence would not be stimulated (or perhaps more correctly, adaptation of disparity vergence which is manifested as a transient [apparent] change in tonic vergence) since sustained bifixation at any fixed near distance has not occurred. However, recently completed work in our laboratory, using visually-normal individuals, has

### NEAR POINT OF CONVERGENCE



**Figure 5.** Phases in the clinical measurement of the near point of convergence. Symbols: T = target, CR = center of rotation of eye, PFA = Panum's fusional area, F = fovea, S = saccade, V = disparity vergence, and LE = left eye.

# HORIZONTAL FUSIONAL VERGENCE RANGES



**Figure 6.** Clinical measurement of positive and negative relative fusional vergence ranges. Symbols: T = target, T' = optical image of target, CR = center of rotation of eye, PFA = Panum's fusional area, f = fovea, BO = base-out prisms, BI = base-in prisms, FD = fixation disparity, ACC = accommodation, and VG-ACC = vergence accommodation.

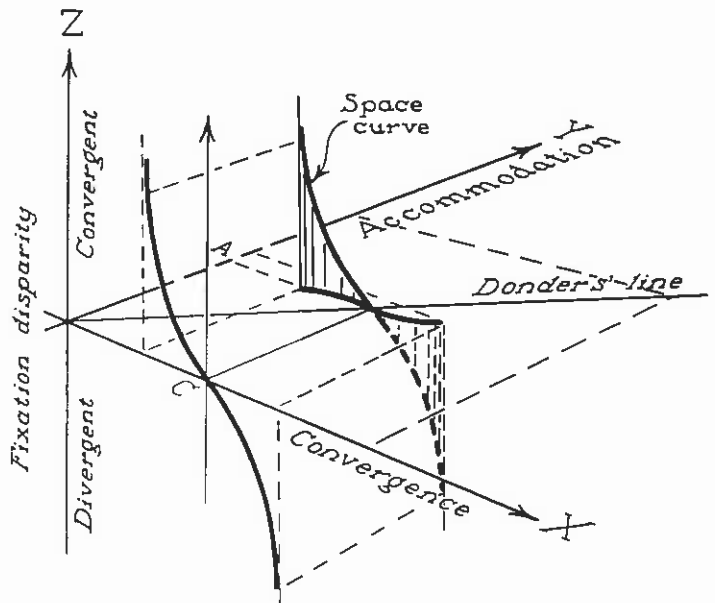
demonstrated that repeated measurement of the nearpoint of convergence and its recovery can indeed transiently affect tonic vergence. Furthermore, in some individuals, especially those with a receded nearpoint of convergence and correlated near symptoms, the increased effort to converge and maintain fusion may be sufficient to elicit a vergence adaptive response. This idea is worthy of careful investigation.

## Relative Fusional Vergence

In determining the nearpoint of convergence or *maximum* vergence ability, the accommodative demand increases in the same manner as the vergence demand as target distance is varied (i.e., congruent stimuli). In contrast, during the testing of *relative* vergence ability, the vergence stimulus is changed while the accommodative stimulus remains constant (i.e., non-congruent stimuli).<sup>30</sup> When performing this test, the clinician slowly introduces changes in the vergence stimulus (constant velocity ramp of disparity), while attempting to elicit an appropriate vergence response (ramps and/or small

steps).<sup>31,32</sup> To maintain target clarity under closed-loop conditions, accommodation must be inhibited. Such clinical testing using non-congruent stimuli has been considered to be an indication of the "flexibility," "independence," "dissociation," "inhibition" or "degrees of freedom" in the linkage between these two oculomotor systems.

The clinical picture for its measurement is depicted in part in Figure 6 for both positive and negative relative fusional vergence. Let us assume at the start of testing that the patient is accurately bifixating target T (a small vertical row of letters to provide optimal stimulation) at 40 cm, so that it is precisely stimulating the center of foveal Panum's fusional area in each eye (Figure 6a). Upon introduction of the base-out prisms, the eyes are forced to increase their vergence angle to maintain sensory fusion of the target which is being optically displaced towards the patient (Figure 6b) (the relatively small apparent change in target distance may also stimulate proximal vergence). This induces an increase in exo fixation disparity (Figure 7),<sup>33</sup> so that the point of bifixation progressively shifts relatively



**Figure 7.** Relationship of the fixation disparity prism curve (Z-axis) and Donder's diagram (X-Y axis). Plot shows that as prism vergence demand (X-axis) is altered at a fixed accommodative stimulus level (A), there is a predicted change in both vergence error or fixation disparity (solid line labelled space curve in Z-axis) and the closed-loop accommodative response (solid curved line in X-Y plane intersecting space curve). C = associated phoria or prism amount for which fixation disparity is zero. In effect, plot shows changes in steady-state vergence and accommodation during conventional clinical testing of relative fusional vergence ranges. Reprinted with the permission of the publisher, from Ogle, Martin and Dyer, 1967.

further from the advancing optical image of the target (but still within Panum's fusional area). Concurrently, the steady-state accommodative response slowly increases (initially within and later outside the depth of focus of the eye) due to increased vergence accommodation, with the amount depending in part on the value of the CAC ratio (Figure 8). Thus, during this test, the vergence-driven accommodation increases while the blur-driven accommodation, which is initially relatively constant and "lags" behind the stimulus (typical for negative feedback control systems), attempts to reduce its output and thereby maintain the perception of clear (and single) vision; the reduced blur-driven accommodation and related accommodative divergence are responsible for producing the increase in exo fixation disparity mentioned earlier. However, at some point, this "backing off" of accommodation is insufficient, and a blurred percept results as the depth of focus is exceeded. With still further non-congruent stimulation and the resultant blur and exo fixation disparity, the image can no longer be fused, and diplopia ensues. See Figure 5d-f for details of the fusional recovery measurement. With regard to base-in relative fusional vergence testing,

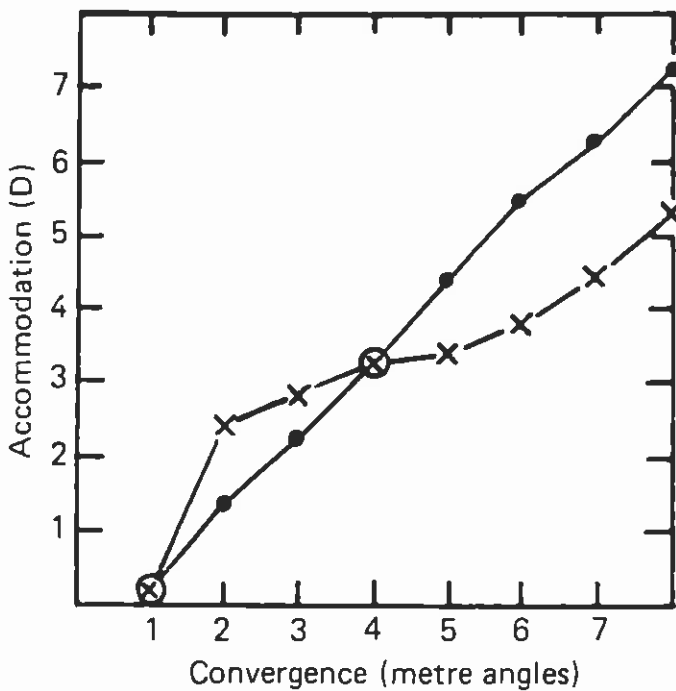


Figure 8. Accommodation as a function of convergence in one young adult. The closed circles show convergence-induced accommodation through 0.5mm artificial pupils, whereas the crosses show the inhibition of convergence-induced accommodation at the same 3 diopter stimulus level through 3mm artificial pupils. Shows the relative impact of vergence accommodation under open-loop and normal closed-loop viewing conditions. Reprinted with permission of the publishers, from Fincham and Walton, 1957.

the scenario is similar to that described above except: (1) eso fixation disparity is found, and (2) vergence-accommodation decreases.

### Prism Flipper

Related to relative vergence range testing is the clinical prism flipper (or "rock") test<sup>34</sup> (Figure 9a). Rather than using ramps and/or small discrete steps of disparity, the prism flipper introduces relatively large steps of disparity (such as 10 BO to 6 BI). Thus, during such testing, there are changes in the vergence stimulus, vergence response, and accommodative response (Figure 9b) as described earlier for relative vergence testing (Figures 7 and 8); the relatively small change in apparent target distance may stimulate proximal vergence, but this is generally not considered in the assessment. Non-congruent conditions are present in both the prism flipper and relative vergence tests. However, the former is regarded as a *dynamic* test in which frequency of the stimulus and correlated system response *change* is assessed over time, while the latter is regarded as a *static* test in which system response *range* is ascertained, and inferences regarding sustained near vision (with comfort) can be made. Further, the large disparity step inputs with the prism

flipper may "stress" an abnormal vergence system more than the small steps used in the PFV/NFV measurement, and therefore has a higher probability of eliciting an anomalous response from an already compromised vergence system. Thus, the prism flipper may have greater diagnostic capabilities.

### CAC Ratio

Although not commonly assessed in the clinic, the CAC ratio can provide insight into the relative strength of the crosslink from the vergence system to accommodation. In contrast to the measurement of relative vergence range and flipper step vergence ability, in which the accommodative system is in the normal closed-loop mode, in the measurement of the CAC ratio, the accommodative system is in the open-loop mode and therefore the full impact of the vergence drive on it is allowed to become manifest (Figure 8). In general, one measures the amount of open-loop accommodation to a change in

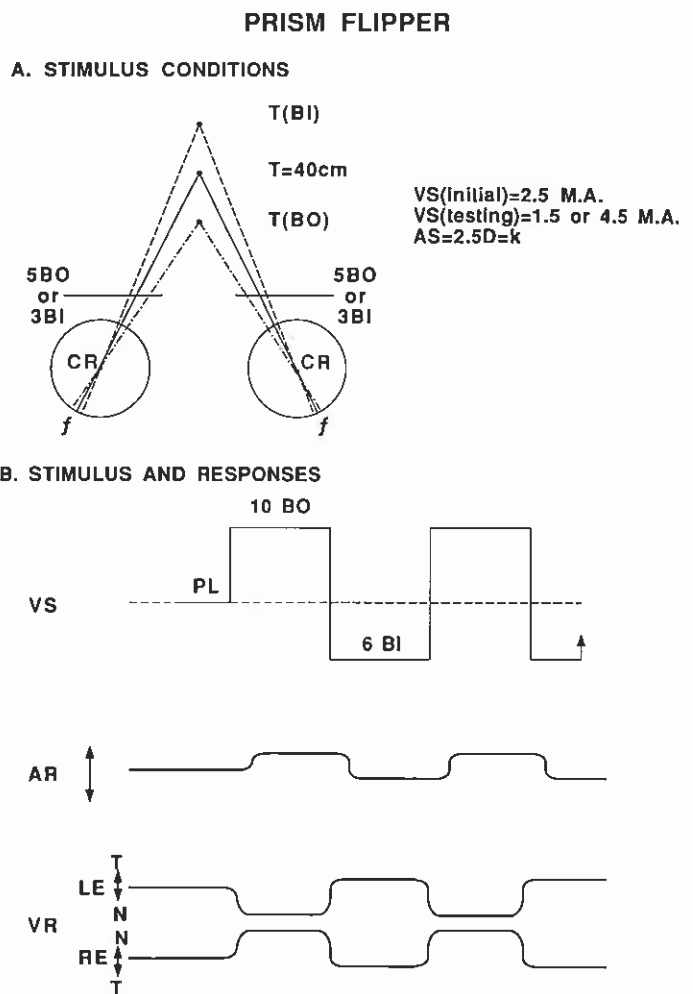
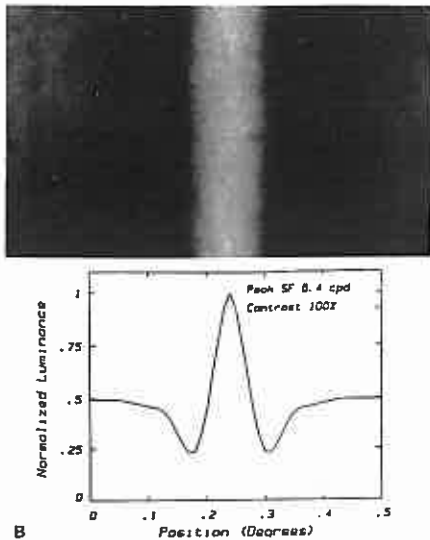


Figure 9. Schematic diagram showing prism flipper dynamic responses. Symbols: T = target, T (BI) = optical image of target viewed through base-in prisms, T (BO) = optical image of target viewed through base-out prisms, CR = center of rotation of eye, VS = vergence stimulus, VR = vergence response, AS = accommodative stimulus, AR = accommodative response, MA = meter angles, k = constant, PL = plano lenses, LE = left eye, RE = right eye, T = templeward, and N = nasalward.

the closed-loop disparity vergence response. Unlike the accommodative system with its relatively low gain,<sup>12</sup> the disparity vergence system has a very high gain and hence relatively little steady-state error (i.e., fixation disparity).<sup>25</sup> In this case, the vergence stimulus and vergence response are essentially equal, and therefore there is no need to differentiate between a stimulus and response CAC ratio. The CAC ratio has been measured experimentally using pinholes before the eyes,<sup>35</sup> but recent introduction of a special "blur-free" grating target (DOG or difference of Gaussians)<sup>36</sup> (Figure 10) obviates the need for pinhole apertures, and therefore this becomes a simpler measure to obtain in the clinic. The clinician might



**Figure 10.** A: DOG stimulus with its diffuse black/white borders resulting in absence of a stimulus to blur-driven accommodation; modified clinical Wesson card without central aperture. Available from Dr. Wesson, University of Alabama, School of Optometry, Birmingham, AL 35294). B: The photometrically measured luminance profile of a DOG. The luminance profile of a 100% contrast DOG obtained directly from a photographic slide with a scanning photometer. Reprinted with permission of the publisher, from Kotulak and Schor, 1987.

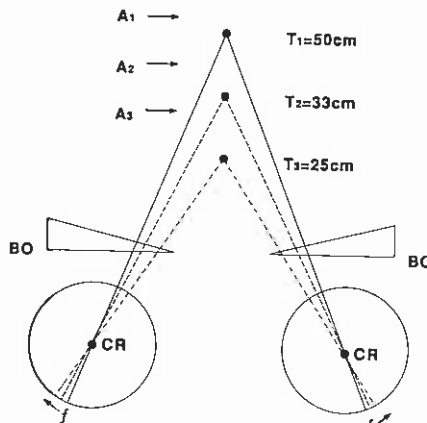
use a Wesson DOG card<sup>37</sup> and perform dynamic retinoscopy with bifixation on the central bright target region at four different near viewing distances to provide varying amounts of disparity stimulation. From this, the amount of convergence accommodation can be determined at each convergence level, averaged (assuming linearity), and the ratio computed (Figure 11). However, since physically moving the target progressively inward may alter the proximal drive and potentially contaminate the measurement, it is better to keep the target fixed at 40 cm and vary the vergence demand using base-out prisms which probably minimizes such an effect. Furthermore, maintaining the target at a fixed distance would keep its spatial frequency components, and therefore their blur-driven effect on steady-state accommodation, constant.<sup>12</sup>

### ACCOMMODATION PRIMARY AND VERGENCE SECONDARY

#### Binocular Amplitude of Accommodation

The binocular amplitude of accommodation represents the dioptric range between the farthest (approximately 0.5 D, assuming a depth-of-focus of  $\pm 0.5$  D) and

### CAC RATIO



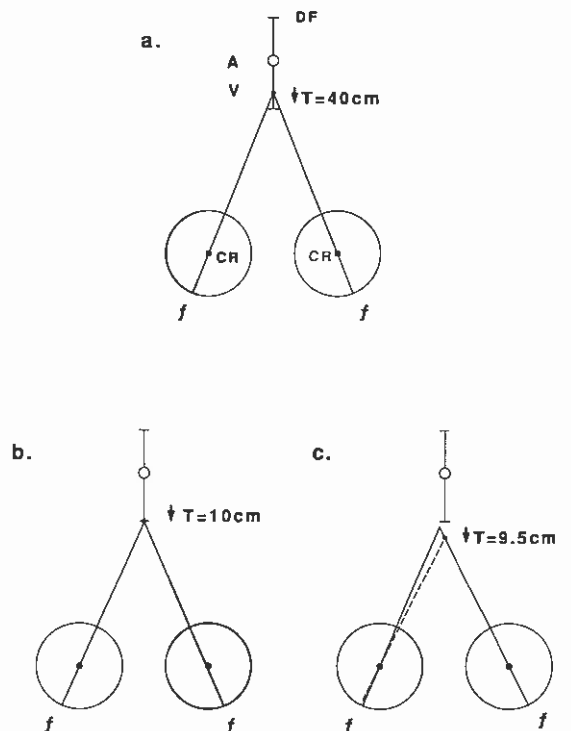
**Figure 11.** Clinical measurement of the CAC ratio. Symbols:  $T_{1,3}$  = target distances,  $A_{1,3}$  = associated accommodative responses, BO = base-out prisms, CR = center of rotation of eye, and  $f$  = fovea.

the (age-dependent) nearest point of clear vision with conjugate focus under normal, fused viewing conditions.<sup>28</sup> However, for simplicity, it is assumed clinically that the farpoint of accommodation is at infinity (zero diopters), and thus the binocular amplitude of accommodation is represented by the closest point (dioptrically) of clear and single vision. This value is frequently approximately 0.5 D greater than the monocular accommodative amplitude, presumably due to added vergence drive to the accommodative system.<sup>28</sup> During this measurement, the binocularly-congruent accommodation and vergence stimulus is brought progressively toward the patient until the occurrence of first, slight sustained blur is reported. Obviously, proximal drive to the two oculomotor systems may be pronounced, although this generally and unfortunately is not considered in the assessment.

The various phases in the clinical measurement of the binocular amplitude of accommodation are depicted in Figure 12. Let us assume that testing commences with a small detailed target which

provides an effective stimulus to both the accommodation and vergence systems. We further specify that the target is 40 cm from the patient, that it is accurately bifoveally-fixated, and finally that it lies somewhat within the proximal edge of the patient's depth-of-field (Figure 12a). Note that the point conjugate to the retina (point A) is not coincident with the target (T), and this distance represents the near "lag of accommodation". As the target is slowly moved closer, both the accommodative response and the accommodative error increase as a result of the proportional control property of the system<sup>38</sup> (i.e. the accommodative error is proportional to the accommodative stimulus). When the target has advanced to 10.5 cm (9.5 D), no further change in actual accommodative response is possible (as the true lenticular limit has been reached), although the target is perceived to be sharply focused since it still remains within the proximal depth of field (same relative positions as in Figure 12a). As the target advances an additional 0.5 cm to 10 cm, it lies just within the depth-of-field and therefore will still be seen clearly (Figure 12b). However, with an addition-

### BINOCULAR AMPLITUDE OF ACCOMMODATION



**Figure 12.** Phases in the clinical measurement of the binocular amplitude of accommodation. Symbols: T = target, A = accommodative response (O), V = vergence response (\*), DF = depth-of-field, CR = center of rotation, and  $f$  = fovea.

al 0.5 cm of forward movement to 9.5 cm, the target would now lie just outside the proximal depth-of-field and therefore be perceived as having slight (sustained) blur (Figure 12c). Clinically, this distance (9.5 cm) converted dioptrically (10.5 D) would represent the binocular amplitude of accommodation. However, based on the definition provided earlier involving the nearest and farthest points of conjugate focus to the retina, the actual binocular amplitude of accommodation would be  $9.5 - 0.5 \text{ D} = 9.0 \text{ D}$ . Lastly, as with the nearpoint of convergence measure (see earlier section), a relative increase in exo fixation disparity (assigned totally to the left eye for simplicity) would probably occur concurrently (Figure 12c).

### Relative Accommodation

During the measurement of the binocular nearpoint of accommodation or *maximum* accommodative ability, the binocularly-congruent accommodation and vergence stimulus is progressively brought closer to the patient along the median plane, until the occurrence of first slight sustained blur is reported. In contrast to the binocular amplitude of accommodation, during the testing of *relative* accommodation, the binocular accommodative stimulus is systematically altered while the vergence stimulus remains constant (i.e., non-congruent stimulus). This is exactly the opposite to what occurs in the measurement of relative vergence ranges. When performing this test of relative accommodation, the clinician introduces either minus (to stimulate positive relative accommodation; PRA) or plus (to stimulate negative relative accommodation; NRA) spherical lenses in 0.25 D steps binocularly. This will elicit an appropriate accommodative response with relatively little resultant change in steady-state vergence response (i.e., fixation disparity is maintained within the foveal Panum's fusional area) under closed-loop viewing conditions. Small changes in apparent target distance may occur during this measurement which could stimulate proximal drive. As with other tests (described earlier) of relative vergence ability in which non-congruent stimuli are also used, the testing of relative accommodation is considered to assess "flexibility," "independence," "dissociation," "inhibition" or "degrees of freedom" in the linkage between accommodation

and vergence.

The clinical arrangement for its measurement is depicted in Figure 13 for both positive and negative relative accommodation. Let us assume at the commencement of testing that the patient is accurately bifixating target T (the central letter of a small horizontal row of Snellen letters to provide optimal accommodative stimulation) at 40 cm, so that it is precisely stimulating the central fovea of each eye (Figure 13a). Upon introduction of minus lenses, the eyes are driven (transiently) in a convergent manner by the increased accommodation and correlated accommodative convergence (Figures 13b and 14). If left in this overconvergent position, the target would fall outside of Panum's fusional area at the fovea, with resultant diplopia. Therefore, there is an immediate compensatory stimulus to negative fusional vergence to regain a fused and stable binocular percept (Figures 13c and 14).<sup>39</sup> However, the negative fusional response only acts to place the target back towards the center of the foveal Panum's area using "least effort" (i.e., "lazy lag of vergence"), resulting in a relative increase in eso fixation disparity (Figure 13d). This relative increase in eso steady-state vergence error would become progressively larger with additional minus lenses, until the target image fell outside of foveal Panum's area in the absence of a compensatory vergence response, possibly resulting in diplopia. However, most patients reject the "distasteful diplopia" in favor of a blurred image, and therefore at this point they would instead cease accommodating to overcome the added minus lens power. The opposite findings would be true for the NRA measure. The combined PRA/NRA range is depicted in Figure 15 which shows this to be greatest over one's typical near working range (2 to 5 meter angles).<sup>35</sup>

### Lens Flipper

Related to relative accommodation range testing is the clinical lens flipper ("rock") test.<sup>34</sup> Rather than using small discrete steps of retinal defocus, this test introduces such a change in relatively large amounts, typically 4 diopters ( $\pm 2 \text{ D}$ ) (Figure 16a). During such testing, there are changes in the accommodative stimulus, accommodative response, and vergence response (Figure 16b) (as

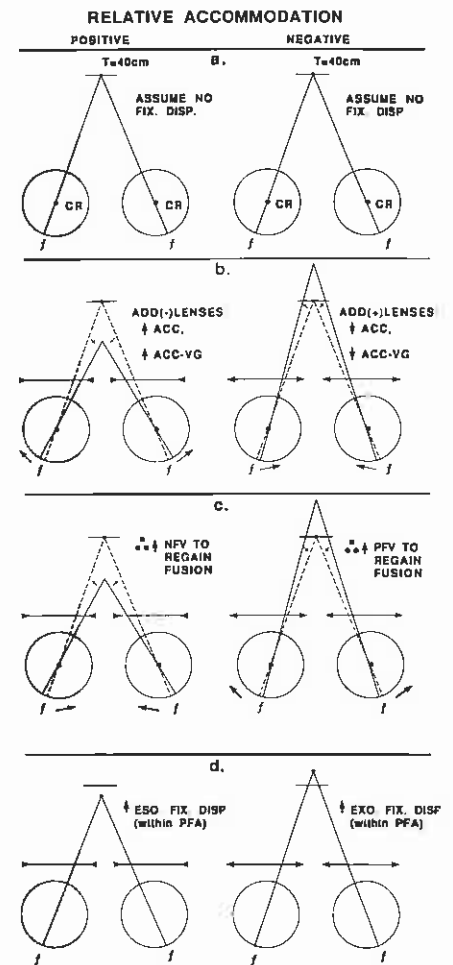
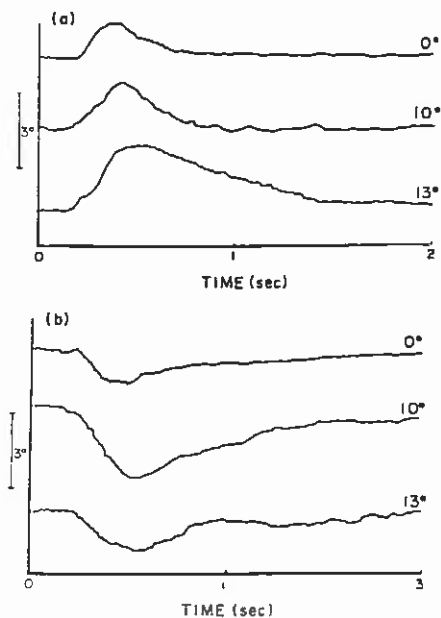


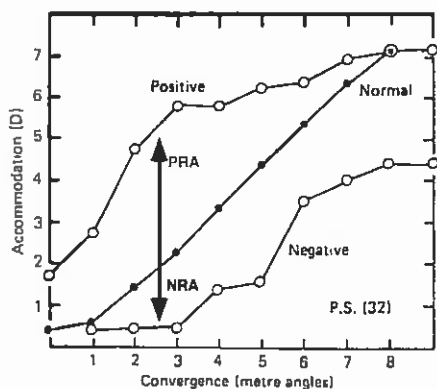
Figure 13. Phases in the clinical measurement of positive and negative relative accommodation. Symbols: T = target, CR = center of rotation of eye, f = fovea, ACC = accommodation, ACC-VG = accommodative convergence, NFV = negative fusional vergence, PFV = positive fusional vergence, and PFA = Panum's fusional area.

described earlier for relative accommodation testing); changes in apparent target distance may occur during this measurement which could stimulate proximal drive. The effect of the lens flipper on the steady-state vergence error as a function of non-congruent (vergence) stimulus demand is shown in Figure 17. Although the non-congruent stimulus conditions are similar in both tests, the lens flipper procedure is regarded as a *dynamic* test, in which frequency of the stimulus and correlated system response *change* is assessed over time, whereas the relative accommodation measure is regarded as a *static* test in which system response *range* is ascertained, and inferences regarding sustained near vision (with comfort) can be made. Lens flipper ability is highly



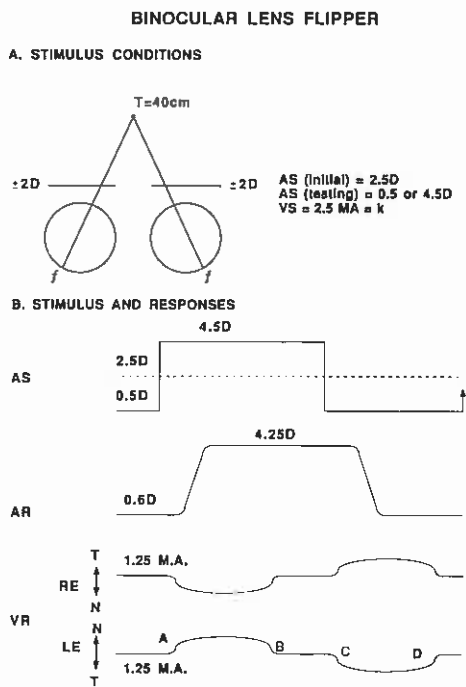


**Figure 14.** Vergence movements produced by binocular accommodative stimulation at three levels of constant disparity vergence stimulation (subject JS). (A) Increasing accommodative stimulation (1-4 diopters). Transient accommodative convergence followed by fusional divergence recovery. (B) Decreasing accommodative stimulation (4-1 diopters). Transient accommodative divergence followed by fusional convergence recovery. Reprinted with permission of the publisher, from Semmlow and Venkiteswaran, 1976.

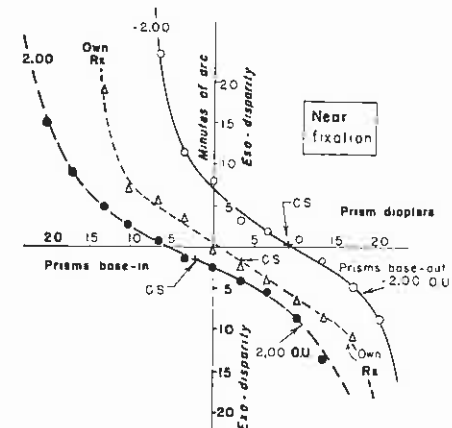


**Figure 15.** Positive and negative amplitudes of relative accommodation at various levels of convergence. Solid circles show normal vergence and accommodation relationship. Reprinted with permission of the publisher, from Fincham and Walton, 1957.

correlated with dynamic step tracking measures obtained objectively in the research laboratory,<sup>40</sup> and thus the clinician can easily obtain an accurate assessment of relative accommodative ability at high demand levels with extremely simple and inexpensive instrumentation. Also, as mentioned earlier for the prism flipper, the lens flipper test may have particularly good diagnostic capabilities since it produces considerable "stress" on the vergence system.



**Figure 16.** Schematic diagram of the binocular accommodative facility test and associated responses. (A) Stimulus conditions. (B) Dynamic responses. Symbols: T = target, f = fovea, AS = step accommodative stimulus, AR = accommodative response, VS = vergence stimulus, VR = vergence response, MA = meter angles, k = constant, RE = right eye, LE = left eye, T = templeward, N = nasalward, A = transient accommodative convergence, B = negative fusional vergence recovery with residual fixation disparity (see Figure 15), C = transient accommodative divergence, and D = positive fusional vergence recovery with residual fixation disparity (See Figure 17).



**Figure 17.** Displacement of the fixation disparity-prism curve when ophthalmic lenses of a given power were worn by the subject. Fixation distance = 29cm. Reprinted with permission of the publisher, from Ogle, Martin, and Dyer, 1967.

### ACA Ratio

One of the most commonly assessed and used functions in optometric practice is the relation between accommodation and accommodative vergence, or the ACA ratio. This measure provides insight into the relative strength of the neural

crosslink from the accommodative system to vergence. Essentially, in performing this test, the disparity or fusional vergence system is made open-loop by the introduction of a vertical dissociating prism before one eye. The stimulus to accommodation is altered (in the fellow eye) either by changing target distance (6m or 0.16 D to 40cm or 2.5 D) or by introducing negative lenses at a fixed near target distance (40 cm). In clinical usage, typically the stimulus ACA ratio is determined. For this measurement, the accommodative response is *not* directly assessed, but rather is assumed to equal the accommodative stimulus, and only the change in correlated accommodative vergence is actually assessed. However, when using nearpoint retinoscopy in the clinic or a research optometer in the laboratory, the response ACA ratio can be ascertained, as now both the change in accommodative vergence and accommodation are determined. In visually-normal individuals, the response ACA ratio is about 10% greater than the stimulus ACA, since the accommodative

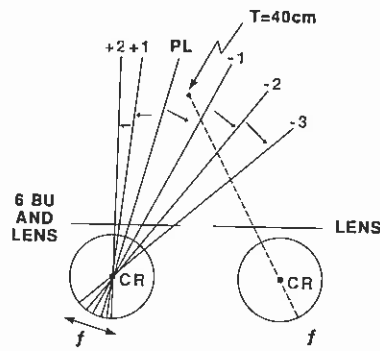
response at near is typically slightly less than the accommodative stimulus.<sup>41</sup> In patients with abnormal binocular vision, this difference may be considerably higher.<sup>42</sup>

There are two basic techniques to measure the stimulus ACA ratio clinically.<sup>28</sup> With the near gradient technique (Figure 18a), the patient is prismatically dissociated, and a small, fine detailed accommodative target at near is provided to the fellow, fixating eye. The phoria with the distance prescription, as well as with the addition of -1, -2, and -3 diopter lenses, is then taken. The use of 4 stimulus levels rather than two allows one to assess the ACA ratio more precisely, as a slope function is being estimated. The accommodative convergence can be measured at each stimulus level and averaged (assuming reasonable linearity), with the result being the ACA ratio.

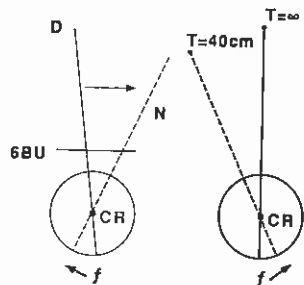
In measuring the ACA ratio using the distance/near phoria technique (Figure 18b), the patient is again prismatically dissociated. However, this time a small,

## ACA RATIO

### A. GRADIENT TECHNIQUE



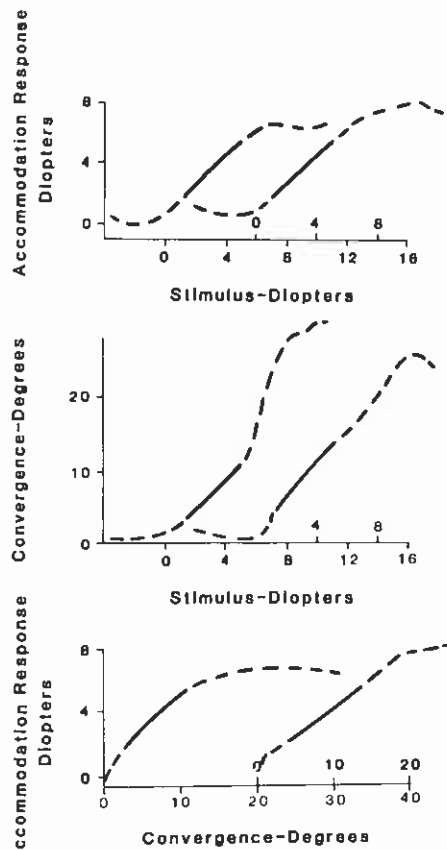
### B. DISTANCE/NEAR PHORIA TECHNIQUE (CALCULATION METHOD)



**Figure 18.** Clinical measurement of the stimulus ACA ratio. (A) Near gradient technique. Note non-linearity of accommodative vergence response with plus lenses. (B) Distance/near phoria technique. Symbols: T = target, CR = center of rotation of eye, f = fovea, BU = base-up prism, D = distance, and N = near.

fine detailed target is presented first at distance and then at near, and the phoria is assessed at these two distances. The ACA ratio is then computed as described earlier. With both techniques, multiple measurements with prism-induced directional alternations (to minimize directional bias effects on this measure) should be obtained and averaged at each stimulus level.

There are some important points to consider in measuring the stimulus ACA ratio in the clinic. First, the near gradient technique, in which spherical lenses are used to alter the stimulus, is preferred over the distance/near phoria technique, in which target distance is physically changed to alter the accommodative stimulus, since proximal vergence may contaminate this measure in the latter case.<sup>28</sup> Second, use of minus lenses is preferred, as here the clinician stimulates only within the linear region of the accommodative stimulus/response function (assuming the accommodative amplitude has not been encroached upon) (Figure



**Figure 19.** (Top) Relation of accommodation response to accommodation stimulus. (Middle) Relation of the accommodative vergence to the accommodation stimulus. (Lower) Relation of accommodative vergence to accommodation response. Results of the experiment in two observers. The straight lines have been determined statistically and represent the linear response region. Reprinted with permission of the publisher, from Alpen et al, 1959.

19).<sup>12,43,44</sup> Also, some clinicians feel that stimulating is more potent than relaxing accommodation to obtain a realistic and useful measure of blur-driven accommodation and related oculomotor responsiveness.

This leads to a point of criticism by some clinicians regarding the minus lens gradient technique: How does one check for plus lens acceptance at near if only minus lenses are used to determine the ACA ratio? The answer is simple. If the clinician desires to assess the ACA ratio accurately, the minus lens near gradient technique is preferred. However, if the clinician wishes to assess the effect of plus lenses on the near phoria, patient comfort, and perhaps relative vergence and accommodation ranges, then the near prescription should be placed in the phoropter or a trial frame, and the appropriate measures

taken. Basically, these are two different measures with two very different goals.

## Concluding Remarks

In the present paper, the sensory, motor, and to some extent, perceptual aspects of the physiology and physiological optics underlying the components of clinical near vergence testing are considered and reviewed in detail along with the elementary application of terminology and concepts borrowed from the control systems approach of bioengineering. While increased understanding of this complex area of vision is in and of itself a lofty and commendable goal, the ultimate end-point of such knowledge by the clinician is enhanced patient care. It is hoped that this presentation has provided the clinician with a fuller understanding of the necessary "tools" to probe *all* aspects of the vergence system to determine normal from abnormal, and then to provide more directed and efficient treatment with careful quantitative monitoring of the appropriate vision functions. Such detailed and expanded investigation of near vision should indeed result in the rendering of improved patient care, including areas of etiology, diagnosis, prognosis and therapy. This notion is consistent with the tradition and goals of the functional optometrist.

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