

Research Note

Modelling adaptation effects in vergence and accommodation after exposure to a simulated Virtual Reality stimulus

A. S. Eadie,¹ L. S. Gray,² P. Carlin¹ and M. Mon-Williams³

¹Department of Physical Sciences, Glasgow Caledonian University, Glasgow G4 0BA, UK,

²Department of Vision Sciences, Glasgow Caledonian University, Glasgow G4 0BA, UK and

³Department of Psychology, Queensland University, Brisbane, Australia

Summary

Natural viewing conditions place equal demands on the vergence and accommodation systems. The two responses are co-ordinated via the interactive components which couple the two systems: accommodative vergence and vergence accommodation. The crosslink components are usually quantified by the AC/A and CA/C ratios. Whether these ratios are stable entities, genetically determined, or modifiable by experience has been the subject of some debate. A 'Virtual Reality' stimulus was used to place unequal demands on the vergence and accommodation systems. Pre-task and post-task measures of AC/A and CA/C were objectively determined. The changes in the post-task measures are discussed with reference to a dual interactive model of vergence and accommodation. Model simulations suggest that adaptation of the vergence and accommodative controllers (tonic adaptation) may also play a part by altering the open loop bias. The results therefore support the idea that vergence accommodation and accommodative vergence are capable of adaptation. © 2000 The College of Optometrists. Published by Elsevier Science Ltd.

Introduction

Two types of adaptation effects have been investigated with respect to the vergence and accommodation systems: adaptation of the controller mechanisms, known as tonic adaptation and adaptation of the crosslinks which interconnect the two systems.

Adaptation of the vergence and accommodation controllers

This type of adaptation occurs when viewing a near object for a prolonged period of time and is a response to temporary changes in environmental conditions. Adaptation of vergence and accommodation is usually manifest as an alteration of the open loop response. In the absence of all stimuli, vergence and accommodation assume residual values of approximately -1 to 1 MA (Hung and Semmlow, 1980; Owens and Leibowitz, 1983) and 0.75 to 1.5 D (Leibowitz and Owens,

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Correspondence and reprints request to: Dr A.S. Eadie.

1978; McBrien and Millodot, 1987) respectively. After sustained exposure to near targets, the open loop accommodation and vergence responses take longer than normal to reach their resting levels (Schor, 1979, 1986; Schor *et al.*, 1984; Wolf *et al.*, 1987; Rosenfield and Gilmartin, 1989; Fisher *et al.*, 1990). These after-effects are indicative of adaptation within the systems.

The first quantitative model of controller adaptation in the vergence and accommodation systems was a model of vergence adaptation (Schor, 1979), based on the observation that disparity vergence has two components: fast fusional vergence which rapidly aligns the eyes and slow fusional vergence which maintains binocular alignment (Rashbass and Westheimer, 1961). The Schor model comprises phasic and tonic elements which correspond to fast and slow fusional vergence respectively and the original model has been extended to include adaptation of accommodation. (Schor, 1992) The phasic element is responsible for the initial response to a change in stimulus and its output feeds the tonic element. The tonic element is in a parallel feedforward loop such that the total controller effort is an aggregate response from the output of the phasic and tonic elements. The phasic component is inversely related to the amount of adaptation and whilst it decays with the onset of adaptation, the tonic contribution increases to maintain the response at the required level. However the Schor model does not simulate 'real' adaptation because the transfer function contains no adaptive elements, i.e. system parameters remain constant and it does not simulate open loop behaviour as the model output decays to zero instead of tonic level under open loop conditions.

The position of the crosslinks has been studied with regard to the effect of tonic adaptation on vergence accommodation (Rosenfield and Gilmartin, 1988a). These authors adopted the terms reflex and adaptive to describe fast fusional and slow fusional components of vergence and reported that vergence accommodation was stimulated by both the reflex and adaptive responses. The Rosenfield and Gilmartin model (Rosenfield and Gilmartin, 1988a), places the crosslinks between vergence and accommodation after the adaptive element. This means that adaptation is stimulated by the output of the reflex element and is not subject to direct crosslink stimulation, although, indirect or secondary stimulation may still occur via the feedback loops. It is believed that this form of adaptation occurs to reduce visual fatigue when viewing targets at higher stimulus levels for a prolonged period of time (Rosenfield and Gilmartin, 1988a,b).

Hung (1992) has proposed a model of vergence and accommodative controller adaptation. This model is an extension of the dual interactive static model (Hung and Semmlow, 1980) in which the accommodative and

vergence controller time constants are modified as a function of the length of time a target is viewed and the magnitude of the controller output. The model has provided a close fit to experimental results with the vergence system closed loop (or intermittently open and closed) and the accommodation system open loop. Adaptation after-effects are modelled by parametric changes within the systems. The results of model simulations suggest no change in the model parameters such as Controller Gain and Bias levels (tonic vergence and accommodation) or the crosslink gains: AC and CA. A change in controller time constant alone serves to produce the adaptation effect in response to prolonged effort from the vergence and accommodation controllers.

Crosslink adaptation

The near triad responds synkinetically to changes in target distance with the crosslinks between vergence and accommodation — accommodative vergence (Alpern *et al.*, 1959) and vergence accommodation (Fincham and Walton, 1957) providing the co-ordination for this response. There has been considerable debate as to whether the crosslink components of vergence and accommodation are amenable to adaptation. With reference to the models described above, the crosslink components of the near response are known as the AC and CA gains which are usually quantified clinically as the AC/A and CA/C ratios. Several reports have suggested that the AC/A ratio can be altered temporarily (Manas, 1958; Flom, 1960; Ogle *et al.*, 1967; Schor and Horner, 1989). It is not known whether these changes are caused by modification of the crosslink components or other components within the systems.

Several studies have considered the possibility of some degree of plasticity in the crosslink components. (Miles and Judge, 1982; Judge and Miles, 1985) An early postulate (Helmholz, 1924) stated that the crosslink components would adapt as a result of developmental changes such as an increase in interocular separation and a decrease in accommodation with age. An increase in pupillary distance (PD) which occurs during childhood would require an increase in vergence for a target at a given distance and one possible explanation is that the effect could be achieved by an increase in the gain of accommodative vergence (AC gain). A corresponding decrease in the gain of vergence accommodation (CA gain) is also required to compensate for changes in vergence-driven accommodation. This explanation provides a plausible mechanism to increase vergence whilst maintaining a constant level of accommodation. A similar argument (Miles and Judge, 1982; Judge and Miles, 1985), is put for-

ward for loss of accommodation with age: accommodative effort can be augmented by an increase in vergence accommodation generated by an increase in CA gain and a corresponding decrease in AC gain to maintain accommodative vergence.

Attempts to demonstrate the plasticity have been made by altering the effective interocular separation using laterally and medially displacing perisopic spectacles (Miles and Judge, 1982; Judge and Miles, 1985; Miles *et al.*, 1987; Fisher *et al.*, 1990; Bobier and McRae, 1996). The results of these experiments, with the exception of Fisher *et al.* (1990), found an increase in AC/A ratio for telestereoscopes after 30 min of use, as predicted, but cyclopean spectacles produced either conflicting results or were found to be ineffective. Fisher *et al.* found no changes in the AC/A ratio but large changes in tonic vergence. Bobier and McRae (1996) however found changes in tonic vergence and the AC/A ratio. Hence, these results produced no conclusive evidence of crosslink adaptation.

The current study aims to investigate the possibility of adaptation of crosslink gains based on the response ratios of AC/A and CA/C using a 'Virtual Reality' (VR) stimulus. Virtual Reality systems place a constant demand on accommodation whilst vergence continuously changes. Experimental conditions which place different demands on the vergence and accommodation systems may result in changes in the crosslinks between the two systems. For example, a continually varying vergence stimulus (e.g. 0–6 MA varied sinusoidally at 0.3 Hz) and a constant accommodation stimulus (e.g. near point), may elicit changes in the crosslink components due to unequal demands placed on each system and their crosslinks. The stimuli are no longer co-ordinated and therefore the responses of each system will no longer be co-ordinated. In addition, the variation in vergence and hence vergence accommodation may create large fluctuations in the accommodation response. It is therefore possible that the crosslinks may alter (e.g. a decrease in CA gain) to suppress this interference. This makes VR systems an excellent method with which to explore the possibility of crosslink adaptation. Other factors may also play an important role under these circumstances. For example, adaptation of vergence and accommodation controllers and fatigue may influence the responses (Miles *et al.*, 1987; Schor and Tsuetaki, 1987).

Methods

Two subjects participated in the study both of whom were 25 years of age. Both subjects were emmetropic and had normal clinical measures of accommodation amplitude, stereoacuity thresholds, AC/A and CA/C ratios. Objective measures of AC/A and CA/C

response ratios were taken before and after the participants had viewed a stereoscopic VR stimulus for 60 min. The stimulus is described in detail below.

Measurement of AC/A and CA/C

The measurement of AC/A requires open loop vergence and closed loop accommodation. Therefore, the measurement was obtained with the subject's left eye occluded. Under this condition, vergence feedback is removed and the accommodative vergence response to accommodation can be measured. The subject viewed a high contrast Maltese Cross (0.5 degree in size) placed in front of the right eye. The target was viewed through a 5 D Badal lens to ensure that a constant retinal image size was maintained (i.e. proximal accommodative are maintained at a constant level). Accommodative demand was altered with ophthalmic trial lenses ranging from 0 D to 6 D in increments of 1 D, introduced in random order.

The measurement of CA/C requires the accommodation system to be open loop whilst the vergence system is under closed loop conditions. This was done using a Gaussian blurred vertical line (0.5 cycles/degree) which stimulates vergence but not accommodation. The target was printed on a 35 mm slide. Vergence and accommodation responses were measured as the vergence stimulus was increased from 0 MA to 6 MA using prisms, introduced in random order. Ten static measures of accommodation were taken at each stimulus level at intervals of 2 sec with a Canon Autorefractometer R-1. Vergence was measured with an IR eye tracker. AC/A and CA/C were measured in random order, the measurements being taken immediately after exposure to the stimulus. The time taken to complete a set of measurements was between three and five min.

Virtual Reality system

The target consisted of two computer generated images presented on a high resolution monitor at a frequency of 120 Hz. The targets were viewed haploscopically through crossed polarisers such that each eye was presented with the arms of a cross (*Figure 1*), which when fused produced a high contrast (80%) cross. The horizontal position of the targets was varied sinusoidally at a frequency of 0.3 Hz to induce sinusoidal vergence stimulus of 0 to 3 MA (subject AS) or 0 to 6 MA (subject BS). The monitor was placed in the plane of the middle of the vergence range i.e. at 1.5 D (subject AS) or 3 D (subject BS). Thus, accommodative demand was constant whilst the vergence demand continually varied. The angular size of the target was kept constant to remove size cues. The extreme stimulus

conditions were chosen to simulate a Virtual Reality System as far as is possible experimentally.

Results

The pre and post task AC/A and CA/C responses for the two subjects are shown in *Figures 2–5*. The differences in the pre- and post-task measures of AC/A and CA/C ratios of both subjects indicate that adaptation effects on the vergence and accommodation systems were produced by the VR stimulus. It should be noted that because the experimental stimuli were subject dependent, the results cannot be compared directly.

The two subjects had difficulty maintaining single vision for the first 10 min of the experiment and had to evoke voluntary effort to obtain a single percept. They also reported that although loss of fusion became less frequent as the experiment progressed, voluntary effort could not always be used to regain single vision. In this case, the subjects had to wait until the target

had completed its cycle before a single percept could be obtained.

Subject BS

After the adaptation task, both the AC/A and CA/C ratios were reduced for subject BS (*Figure 2*). The CA/C ratio was reduced from 0.3 D/MA to 0.1 D/MA and the AC/A ratio was reduced from 0.56 MA/D to 0.03 MA/D (*Figure 3*).

The lower gain of the post task AC response shows that open loop vergence is less sensitive to changes in accommodation and the high intercept indicates that vergence has experienced a large shift in magnitude. The lower gain of the open loop accommodation response indicates that open loop accommodation is less sensitive to changes in vergence and has adopted a position close to the resting level of accommodation. Thus, after the adaptation task, the interaction between vergence and accommodation has been reduced.

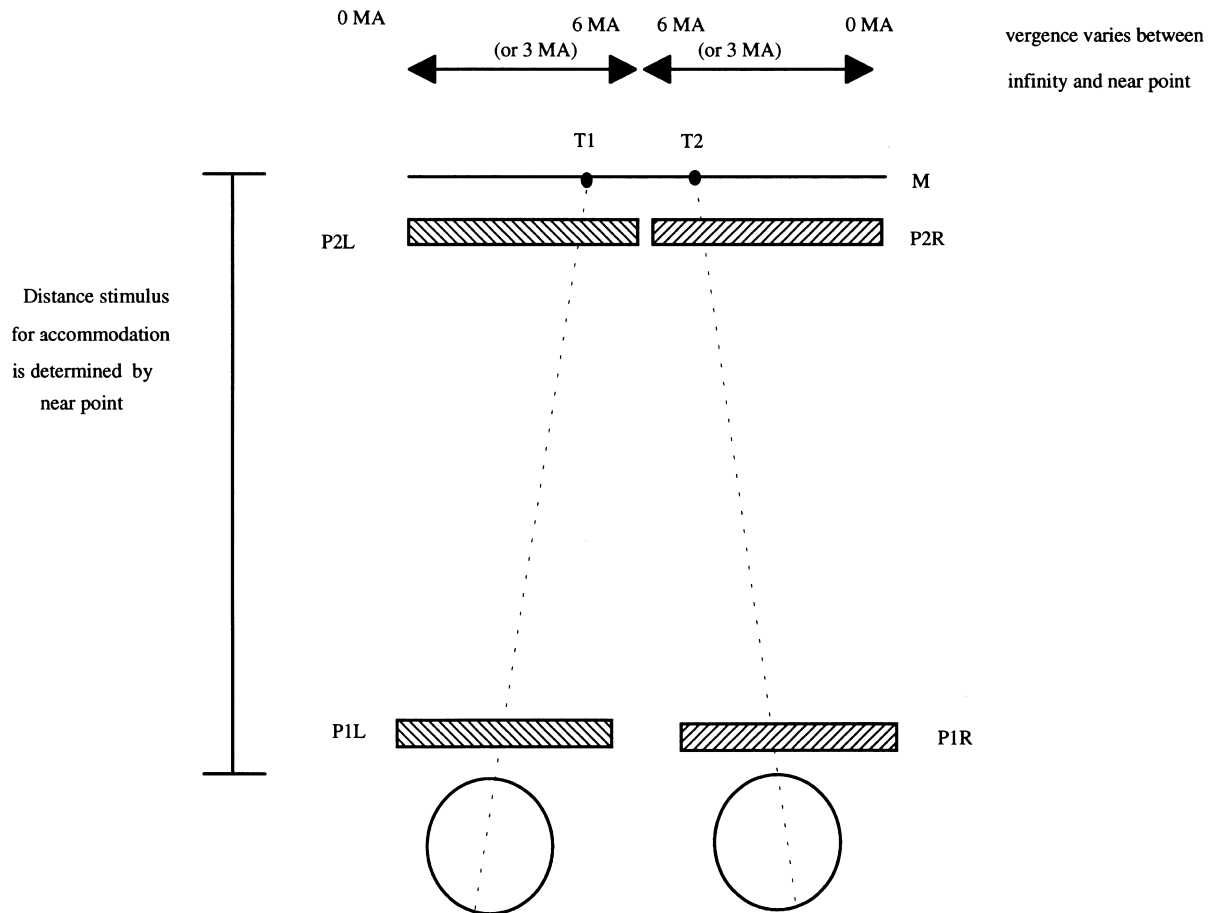


Figure 1. Virtual Reality stimulus. M — high resolution computer monitor; P1L, P1R, P2L, P2L — polarisers; T1 and T2 — targets.

Subject AS

The CA/C ratio has been reduced from 0.87 D/MA to 0.45 D/MA after adaptation (*Figure 5*). The post-task AC/A response for this subject is more difficult to interpret (*Figure 4*). Although the response levels are lower, the spread of the data could be interpreted as either a flat response, a high gain response or a non linear saturated response. The approach taken however was to discard the first two data points on the graph. This is justified by the fact that the subject experienced diplopia at the conclusion of the experiment. Using this approach the AC/A ratio was reduced from 1.02 MA/D to 0.6 MA/D. Both subjects therefore display a similar response to the effects of the VR stimulus.

Table 1. Model parameters used to simulate the dynamic response to VR stimulus

Model parameters (dynamic responses)	
Accommodation controller gain	10
Accommodation bias	0.5 D
Vergence controller gain	150
Vergence bias	0.6 MA
Panum's fusional area	0.2 MA
Depth of focus	0.2 D

Modelling

The possible interpretations of the results described above were investigated by model simulations of a

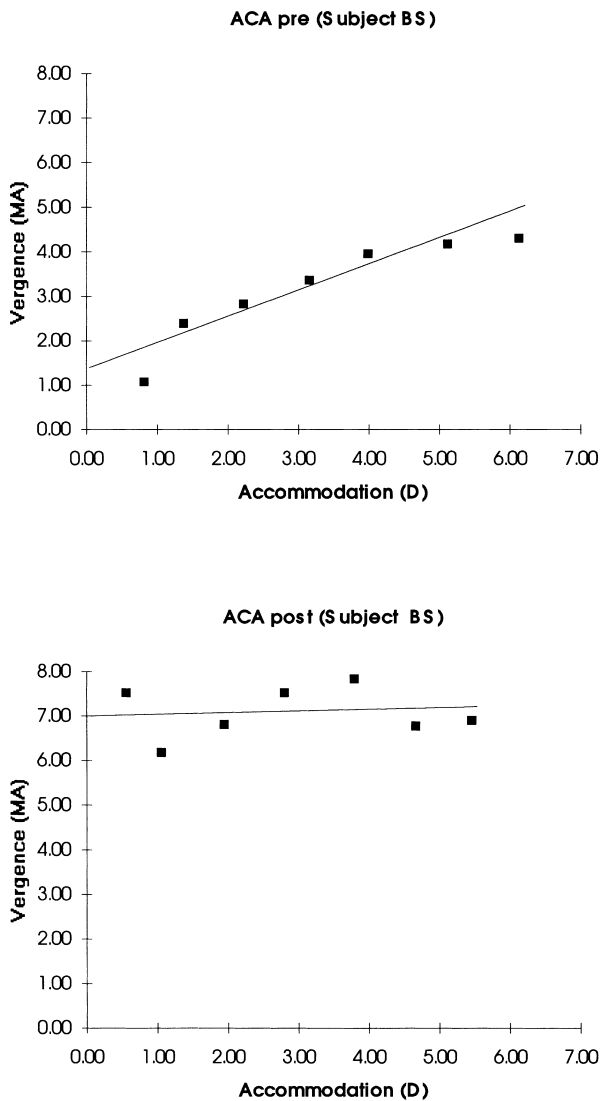


Figure 2. Pre- and post-task AC/A graphs (experimental results — subject BS). Pre-task AC/A — 0.56 MA/D, Post-task AC/A — 0.03 MA/D.

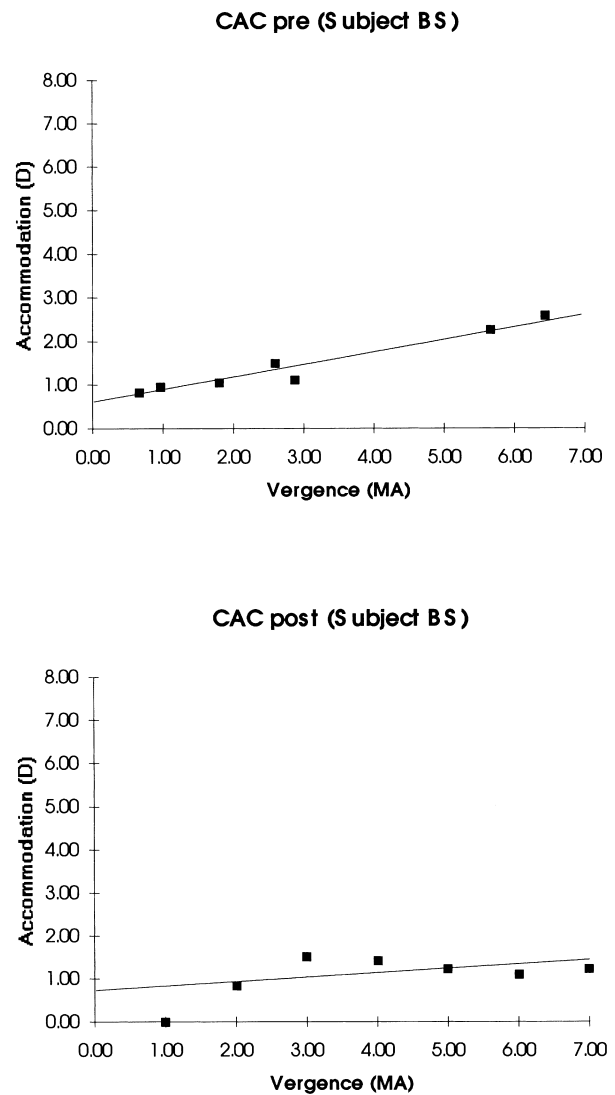


Figure 3. Pre- and post-task CA/C graphs (experimental results — subject BS). Pre-task CA/C — 0.3 D/MA, Post-task CA/C — 0.1 D/MA.

dual interactive model of vergence and accommodation (Hung and Semmlow, 1980) shown in *Figure 6*.

The model parameters used are shown in *Table 1*.

Dynamic response

To investigate the effects of a VR stimulus on the dynamic response of the model, vergence was varied sinusoidally between 0 and 6 MA whilst the accommodation stimulus was constant (6 D). The values of AC and CA gains were altered to observe the effect that these components have on the outputs of the systems. Unity values of AC and CA gains produce almost identical vergence and accommodation responses. The similar responses between

vergence and accommodation indicate almost complete co-ordination between the two systems (*Figure 7a*) and the constant accommodative demand is ignored. The amplitude of the oscillations in the accommodation response are approximately 2.5–3 D, which undoubtedly would result in a blurred accommodative target. One possibility of explaining the effects is to investigate the effect of reducing the AC and CA gains. When the AC and CA gains are decreased (AC=CA=0.8), the interaction between vergence and accommodation is decreased (*Figure 7b*). This has little effect on the vergence response although a marked change in accommodation is produced. Although there are still large fluctuations (up to 2 D) the accommodation

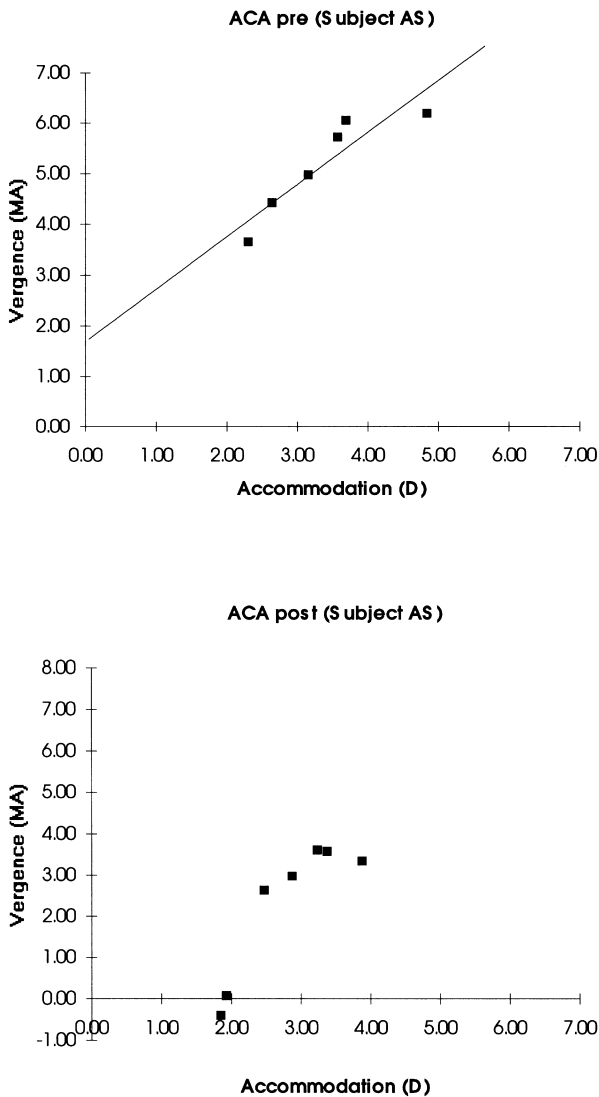


Figure 4. Pre- and post-task AC/A graphs (experimental results — subject AS). Pre-task AC/A — 1.02 MA/D, Post-task AC/A — 0.6 MA/D (using the last five points).

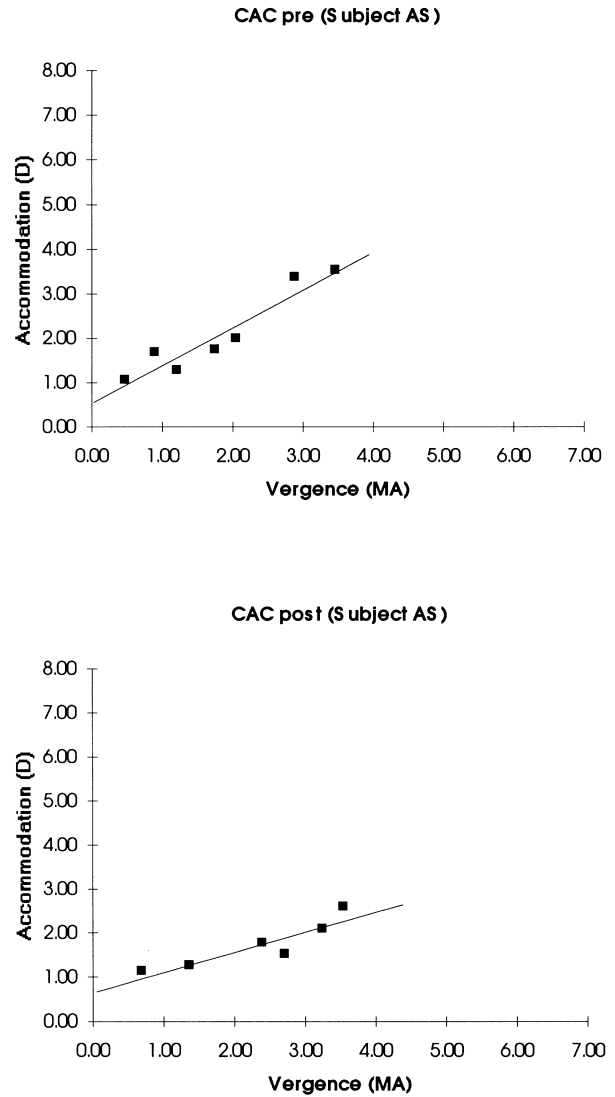


Figure 5. Pre- and post-task CA/C graphs (experimental results — subject AS). Pre-task CA/C — 0.87 D/MA, Post-task CA/C — 0.45 D/MA.

response has an offset of approximately 5 D. This value is similar to the normal static response to a 6 D stimulus. The amplitude of the oscillations is relatively large and would still produce a blurred retinal image. It is only when the gain of the crosslink components are substantially reduced ($CA=AC=0.1$) that the oscillations in the accommodation response are also reduced to an acceptable level (*Figure 7c*). It should be noted that for the sake of clarity, the simulations do not include either miniature eye movements or microfluctuations of accommodation. Inclusion of these components in the model would lead to further increases in the amplitude of the oscillations. The dynamic model simulations demonstrate the effects of a VR system on the vergence and accommodation responses. A constant accommodative response can only be maintained when the interaction between vergence and accommodation is decreased by a substantial reduction in the gain of crosslink components.

In summary, large fluctuations in disparity create large fluctuations in vergence accommodation when normal values of AC/A are used. The variations in accommodation are obviously beyond the tolerance needed to maintain clear vision. When low values of AC and CA gains are substituted in the model the out-

put of the vergence system is similar to before, but there is a dramatic reduction in the oscillations of accommodation.

Modification AC/A and CA/C ratios (adaptation of crosslink gains)

Following on from the results of the dynamic simulations, the model was used from optical infinity to 0.16 m (0–6 D and 0–6 MA) using high and low values of CA and AC gain ('high' = 1, 'low' = 0.1), to simulate the pre- and post-task parameters of AC/A and CA/C. The response ratios of CA/C and AC/A were computed from the result of model simulations. These are shown in *Figures 8 and 9*. Clearly, the effect of reducing the values of AC and CA has produced lower AC/A and CA/C response ratios. Altering these parameters alone however does not explain the experimental data. The offsets found in the experimental data could not be produced in the model simulations by simply altering the crosslink gains.

The effects of tonic adaptation

Due to the length of time subjects were exposed to the adaptation stimulus, it is possible that tonic adap-

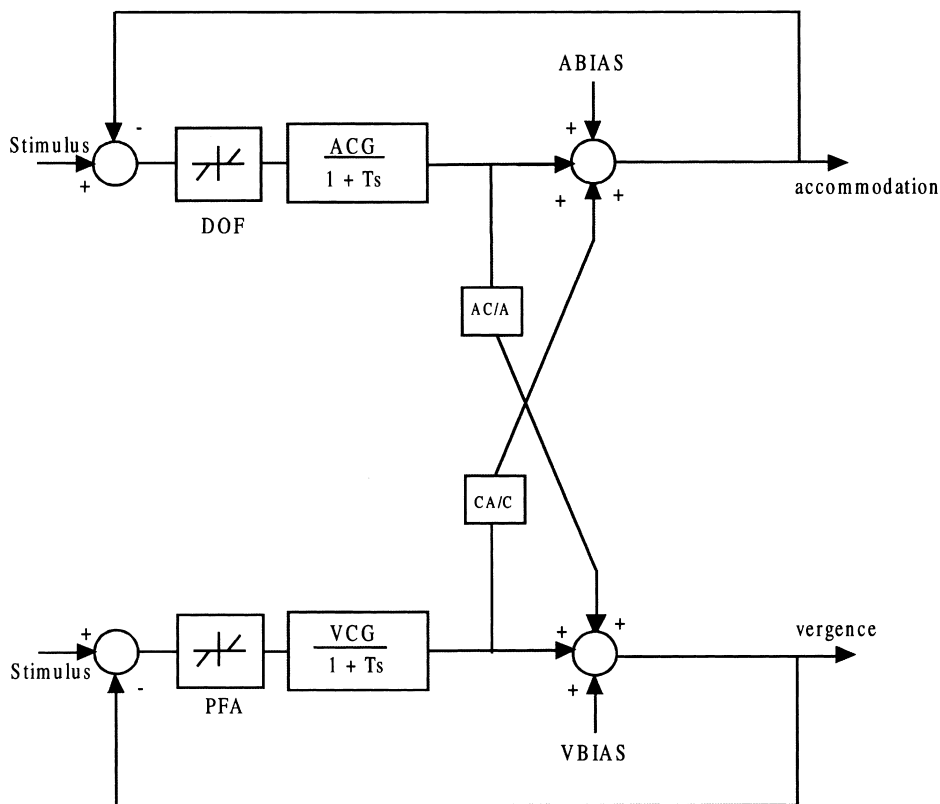


Figure 6. The Hung and Semmlow model of accommodation and vergence (1982).

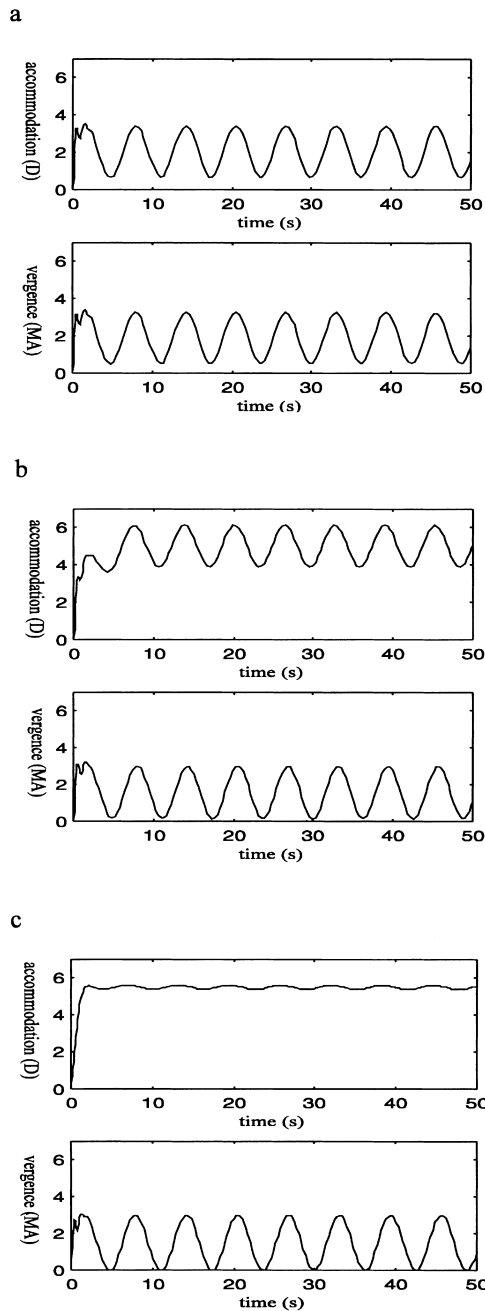


Figure 7. Output of model simulations of the dynamic effects of changes in crosslink gains. (a) AC/A=1, CA/C=1; (b) AC/A=0.8, CA/C=0.8; (c) AC/A=0.1, CA/C=0.1.

tation may also have occurred. Tonic adaptation manifests itself as an increase (i.e. an offset) in the open loop responses. The offset in the post task measurements of AC/A and CA/C where vergence and accommodation respectively are open loop could be the result of tonic adaptation. To investigate the possible effect of tonic adaptation at the conclusion of the experiment, the adaptation was modelled on a static basis by a constant input to the model after the con-

troller and before the crosslinks (Hung, 1992). Model simulations were performed as described above and the AC/A and CA/C responses plotted. The results for the model simulations using the AC and CA parameters of subject MB and constant inputs of 5 D and 1 MA for accommodative bias and vergence bias are shown in *Figure 10*. It can be seen that the results of *Figure 10* closely match the post task experimental results shown in *Figures 2 and 3*.

Discussion

The experimental data confirm that a simulated VR stimulus can induce changes in the crosslink interaction between vergence and accommodation. In these circumstances, model simulations provided a useful method to explore possible explanations of experimental results.

Simulation of the dynamic responses to the VR stimulus showed that normal crosslink activity whilst viewing the VR stimulus would result in an unacceptable level of retinal blur. The subjects, however, were able to obtain single clear images during the adap-

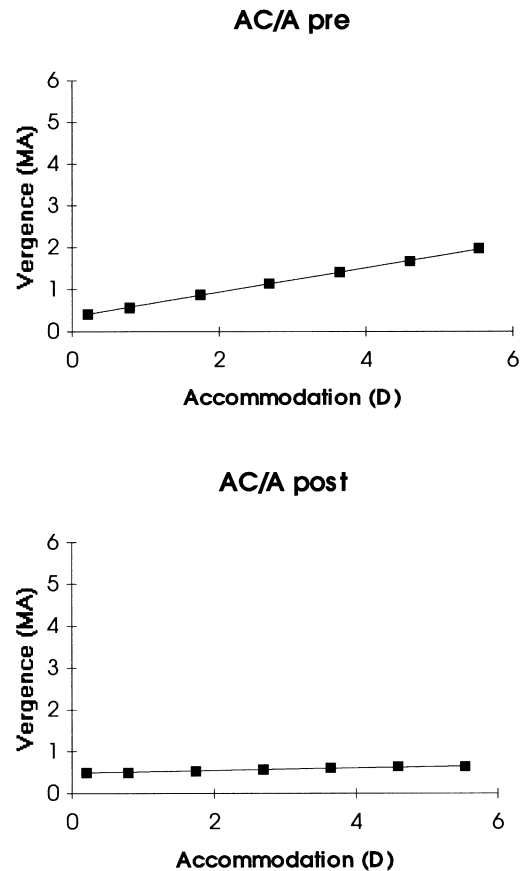


Figure 8. Model simulations of pre- and post-task AC/A. (a) pre task AC/A=1; (b) post task AC/A=0.1.

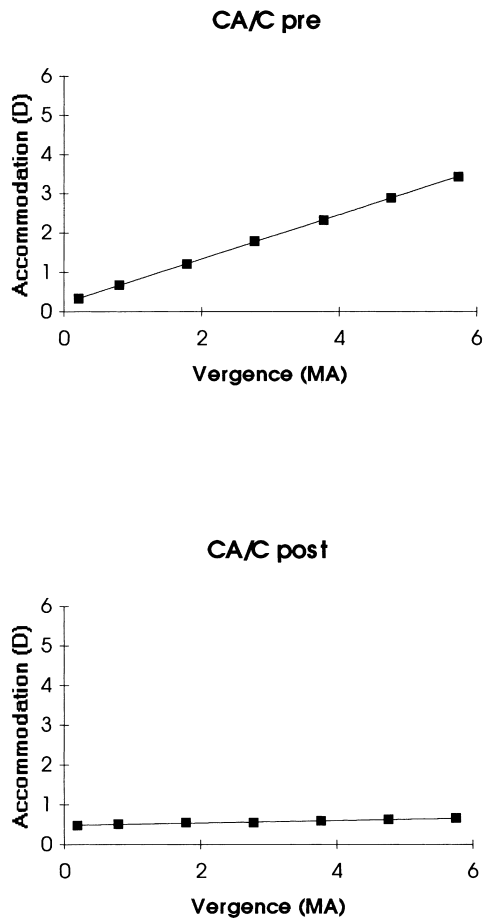


Figure 9. Model simulations of pre- and post-task CA/C. (a) pre task, CA/C=1; (b) post task, CA/C=0.1.

tation task which suggests that their crosslink interaction had altered. Obtaining single clear targets may be a prerequisite condition for an effective adaptation stimulus. The inconclusive results of a previous attempt to alter crosslink behaviour using cyclopean spectacles may have been due to the subjects' difficulty in obtaining single clear targets (Miles *et al.*, 1987). This indicates that vergence and accommodation were not adequately stimulated by cyclopean spectacles for adaptation to take effect. Therefore, the single clear images obtained during the adaptation task of the present study indicate that the VR system is an effective stimulus.

A static model of vergence and accommodation was used to investigate which components within the systems could be altered to produce the changes in AC/A and CA/C ratios found experimentally. Model simulations show that the experimental results cannot be explained solely by a change in the crosslink gains because there also appears to be a change in bias. It is proposed that the change in bias is the result of tonic adaptation induced by the prolonged VR stimulus.

This is consistent with the findings of both Fisher *et al.* (1990) and Bobier and McRae (1996) discussed in the introduction. Tonic adaptation was included in the static model by introducing an offset into the open loop vergence and accommodation responses to simulate the biasing effect.

Conclusions

A VR stimulus places unequal demands on the vergence and accommodation systems which no longer require the co-ordination observed under normal binocular conditions. Indeed, the crosslinks themselves may hinder the vergence and accommodation responses to a VR stimulus. These conditions are not encountered in a natural visual environment and illustrate the versatility of the vergence and accommodation systems.

This study has demonstrated that a VR stimulus can initiate changes in the crosslink interaction between vergence and accommodation by altering the AC/A

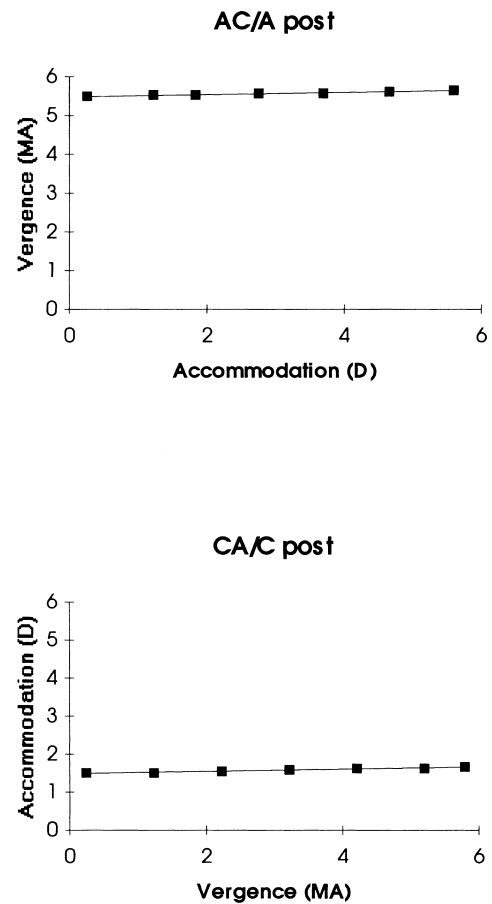


Figure 10. Post-task model simulations of AC/A and CA/C. Model parameters were obtained from the normal values of vergence and accommodation responses and the experimental results of subject MB.

and CA/C ratios. Control theory modelling was used to investigate which system parameters could elicit these changes. Changes in crosslink gains could not reproduce experimental data. It was only when the effects of tonic adaptation and changes in the crosslink gain were included that the results of model simulations were similar to experimental data. This substantiates the idea of crosslink plasticity.

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