The Dissociability of Accommodation From Vergence in the Dark

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The theory that accommodation and vergence are undissociable, except for the limited degree of independence made possible by fusional vergence, has come under increasing attack in recent years. Three independent studies have shown that the tonic or resting states of accommodation and vergence, which were assumed in the studies to be the same as the “dark focus” and the “dark vergence” positions respectively, are only weakly correlated. In addition, Bohman and Saladin have demonstrated that a patient’s dark accommodation position cannot be predicted from his AC/A (accommodative convergence to accommodation) ratio and his dark vergence value. Finally, it has also been shown that the illusions of size, distance and motion that occur when the stimulus is degraded are correlated with dark vergence but not with dark accommodation.

In this paper we present a convincing demonstration of dark dissociation in which accommodation continually moved in one direction, while at the same time vergence paradoxically moved in the opposite one. To do this critical experiment, we used an infrared eye-movement monitor and a dynamic infrared optometer. But the key to achieving the paradoxical effect in the dark was the choice of the initial experimental conditions in the light; the accommodative stimulus was increased until the accommodative response reached a level that was about 1 diopter (D) greater than the mean, dark level, while the eyes were made several prism diopters (PD) more divergent than their typical posture in the dark by opening the vergence loop (by occluding the left eye). In this way, if the dark-dissociation theory were correct, the eyes would converge in darkness despite the ever-decreasing level of accommodation. All three subjects tested in this manner exhibited the dark-dissociation paradox, thus affirming the theory that accommodation and vergence become uncoupled in the dark.

To test whether dark dissociation would occur in the absence of predisposing conditions, a modified version of the above experiment was run, in which the initial accommodative response (in the light) was moved distal to the dark focus position. For the two subjects tested, both the dark responses proceeded in the same direction, but convergence increased so much more than accommodation (270% and 750% respectively), that to explain the increase in convergence by the increase in accommodation, the subjects would have needed response AC/A ratios of 16/1 and 50/1 respectively, whereas their actual ratios were 4/1 and 6/1 respectively. Thus, both versions of the experiment...
Fig. 1. A top view schematic illustrates the apparatus that was used to control the initial stimulus conditions (in the light) for accommodation and vergence and in which the accommodative and vergence responses were measured in the dark. The accommodative stimulus was delivered to the right and left eyes through separate Badal optometers. The targets were 35-mm color slides, located in slide trays at TR and TL, which were each backlighted by a light source that consisted of a filament F and two condensing lenses (C), separated by an aperture P. A diffuser O was placed between each light source and its slide (not shown for the left eye). The right eye target was imaged between collimating lens CLR and Badal lens MBR. Mirror MR1 was stationary while MR2 and MR3 were moved in unison by the mirror drive AS. The closer MR2 and MR3 were brought to the Badal lens MBR, the greater the stimulus to accommodation. The subject’s entrance pupils were positioned at the posterior focal points of their respective Badal lenses. A beamsplitter BS permitted the subject to view the target, while at the same time an infrared beam from the response-measurement optometer (OPT) entered the subject’s eye. The left eye target was placed in slide holder TL. When necessary, the stimulus to accommodation for the left eye could be altered by moving TL either closer to or farther from Badal lens MB. The vergence stimulus was controlled asymmetrically by a mechanical arm VS from an X-Y plotter, which changed the lateral position of TL. The vergence response was monitored by spectacle-mounted, infrared sensors IS.

confirm that the synkinesis that exists between accommodation and vergence in the light is disrupted in the dark.

In addition, the time courses of the dark decay of accommodation and of vergence were drastically different, having in common only their very great length, usually ranging from 10–30 sec.

These results suggest an independence between tonic accommodation and tonic vergence in the dark, but they do not exclude some form of mutual interaction between the two systems, which would presumably occur through accommodative vergence and/or vergence accommodation. In search of a persistent cybernetic link between accommodation and vergence, we looked for a correlation between the tiny fluctuations that occur continuously in both responses in the dark. Fourier analysis of time histories of dark accommodation and dark vergence did in fact reveal a striking similarity between the two noise spectra in a frequency band that extended from 0.19–0.38 Hz. The phase relationship between the two waveforms in this frequency range, obtained from a cross-correlation analysis, varied among subjects, but in most cases accommodation was delayed 2–122 degrees. Although this finding is open to differing interpretations, one that must be considered is that vergence accommodation persists in the dark despite the dissociation of tonic accommodation from tonic vergence.

Materials and Methods

Visual Stimulus

The target that was used for the initial conditions (in the light) of the dark dissociation experiment was a difference of Gaussian (DOG) that had a center spatial frequency of 6.4 cpd, a contrast of 100%, a full bandwidth at half height of 1.75 octaves, and a mean luminance of 10 cd/m2.10

Apparatus

Two serially arranged opto-electronic systems, one for stimulus presentation and the other for response measurement, were used (Fig. 1). The former was capable of independent control of the inputs to the accommodative and vergence systems. The latter was capable of continuous and simultaneous monitoring of the outputs of both systems and of producing high-resolution recordings.

The stimulus to accommodation was generated on a stepping-motor operated Badal optometer,11 and the accommodative response was measured on a dynamic, infrared optometer.12,13 The problem of eye-movement artifacts, which is common to dynamic infrared optometers in general,14 was exacerbated during the measurement of accommodation in the dark, during which time the eyes had a tendency to drift. The subjects...
were trained to hold the right (measured) eye stationary to within a ±0.5 degrees range in which accommodative measures varied less than 0.05 D (one small division on Fig. 2) with changing eye position. With 4-mm pupils, subjects had to move their eyes ±1.5 degrees to produce any noticeable change in accommodative response on the strip chart recorder. To insure that the eye before the dynamic infrared optometer remained stationary, a four-channel strip-chart recorder was used, in which the movements of each eye were monitored separately, while at the same time accommodation and vergence were also recorded (but only the latter two responses are shown in the results). The restricted position of the right eye resulted in asymmetric vergence movements of the eyes. Normally, asymmetric vergence involves an addition of version and vergence innervation, which is thought to occur at the muscle-globe plant. This implies that combined version and vergence movements are processed independently. Consequently, the vergence innervation is predicted to have the same open loop influence on accommodation during symmetric and asymmetric vergence stimulation.

The eye movements were measured with an infrared eye-movement monitor. The sensor assembly was mounted on a pair of spectacle frames that were worn by the subjects. The infrared sources and the photodiodes were carefully adjusted to avoid crosstalk with the infrared optometer. The vergence signal was derived from the lateral movements of each eye by means of an independent differential amplifier, which had the effect of cancelling out conjugate eye movements.

Experimental Procedures

The pupils were dilated with two drops of 2.5% phenylephrine (to insure that the pupil size remained above 3 mm, the minimum required for the dynamic, infrared optometer), and a headrest and a mouthbite were also used for artifact abatement. The use of a much stronger dosage of phenylephrine (10%) was found to have no effect on the resting focus of accommodation. For all subjects, both traces showed regular oscillations; accommodation was typically characterized by large amplitude, low frequency fluctuations, whereas a decrease in accommodation or a divergent eye movement is indicated by a downward deflection of the appropriate trace. For all subjects, both traces showed regular oscillations; accommodation was typically characterized by large amplitude, high frequency fluctuations and vergence by small amplitude, low frequency fluctuations.

Figure 2 contains representative strip-chart recordings of the dark accommodation and vergence of five subjects. Accommodation is given by the lower trace and vergence by the upper one. An increase in accommodation or a convergent eye movement is indicated by an upward deflection of the appropriate trace, whereas a decrease in accommodation or a divergent eye movement is indicated by a downward deflection. For all subjects, both traces showed regular oscillations; accommodation was typically characterized by large amplitude, high frequency fluctuations and vergence by small amplitude, low frequency fluctuations.

For the initial conditions of the dark dissociation experiment, the room lights were turned out, and the vergence loop was opened by extinguishing the light source of the left eye. The accommodative loop of the right eye was closed. Each subject was informed of the nature of the procedure and their informed consent was obtained prior to their participation in the study. For three subjects (subjects 1, 2, 3) the accommodative stimulus was placed 1 D proximal to the resting focus, and for two subjects (subjects 4, 5) it was placed 1 D distal. After 5 secs, the light source for the right eye was turned out. For the next 30–60 sec, dark accommodation and dark vergence were monitored.

Recordings were analyzed quantitatively for all but one subject (subject 2) who was unavailable at the time the digital processing equipment had been developed. The accommodative and vergence signals were run through a lowpass analog filter, which had a -3 dB rolloff at 15 Hz. The filtered outputs were recorded on magnetic tape with an FM deck, using two high resolution channels (with center carrier frequencies of 4000 Hz) and simultaneously on a 4-channel strip-chart recorder. The magnetic tape recordings were used for the cross-correlation analysis, and the strip-chart recordings were used for the time-domain analysis of the dark-dissociation experiment. The tape recordings were played back into an oscilloscope to inspect for artifacts, which were recognizable as a sudden saturation of the signal. Artifact-free segments were digitized by an A-D converter at a rate of 32 samples per sec. Twenty seconds of data were used for the cross-correlation analysis, which was done on a digital computer.

Results

Dark Dissociation Experiment

Figure 2 contains representative strip-chart recordings of the dark accommodation and vergence of five subjects. Accommodation is given by the lower trace and vergence by the upper one. An increase in accommodation or a convergent eye movement is indicated by an upward deflection of the appropriate trace, whereas a decrease in accommodation or a divergent eye movement is indicated by a downward deflection. For all subjects, both traces showed regular oscillations; accommodation was typically characterized by large amplitude, high frequency fluctuations and vergence by small amplitude, low frequency fluctuations.

Figure 2a is for subject 2, an emmetropic young adult who had normal binocular vision. At t = 3 sec, when the lights were turned off, accommodation began to decrease while the eyes converged. The decay of accommodation required about 3 sec, while vergence required about 20 sec.

Subject 3 (Fig. 2b) was another emmetropic young adult who had normal binocular vision. The lights were extinguished at t = 2 sec. Vergence required about 10 sec to reach its tonic level, whereas accommodation took about 5 sec.

Figure 2c is the record for subject 1, a young adult who had about 4 D of hyperopia bilaterally. As a con-
Fig. 2. Strip-chart records of dark accommodation and dark vergence of five subjects. Accommodation is given by the lower trace and vergence by the upper one. An increase in accommodation or a convergent eye movement is indicated by an upward deflection of the appropriate trace, while a decrease in accommodation or a divergent, eye movement is indicated by a downward deflection. Units for accommodation and vergence are diopters (D) and prism diopters (PD) respectively. A through E show subjects 1 through 5 respectively.
sequence, in the absence of his ophthalmic correction, this subject was considerably esophoric. Therefore, when the vergence loop was opened (not shown), he immediately began to converge. This continued when the lights were turned off at t = 0 sec and lasted for about 25 sec. His accommodation changed little but was still decreasing at t = 35 seconds.

Figures 2d–e are the strip-chart records for the two subjects for whom the initial accommodative response was distal to the resting focus and whose accommodation increased in the dark while the eyes converged.

Subject 4 (Fig. 2d) was mildly myopic and was an intermittent exotrope. When the vergence loop was opened (not shown), this subject’s eyes diverged about 10 PD. However, when the lights were extinguished at t = 1 sec, the dark vergence response began immediately and proceeded so rapidly that it was almost complete before accommodation changed. Even if the delay time courses were not so disjunctive, the magnitude of the vergence movement was too large (16 PD) when compared to the size of the accommodative increase (1 D), to be explainable as accommodative vergence (the subject’s response AC/A ratio in the light was 4/1).

Figure 2e is the record for subject 5, who had normal binocular vision but who was mildly myopic. The amplitude of accommodation of this 38-yr-old subject was somewhat reduced due to physiologic age-related changes. At t = 0 seconds, the lights were extinguished. Over 35 sec, the eyes gradually converged about 15 PD, while accommodation increased only about 0.3 D. At this rate, for every diopter of dark accommodation there would be 50 PD of dark vergence. The subject’s actual response AC/A ratio in the light was about 6/1, suggesting that accommodation and vergence went to their resting states independently in the dark.

Cross-Correlation Analysis

Figure 3 represents the Fourier power spectra of dark accommodation and of dark vergence for four subjects. Equivalent scales for accommodation and vergence have been used to facilitate direct comparisons (1 D of accommodation = 1 meter angle of vergence). For each subject, the power has been normalized to the highest peak. The noise of dark accommodation (solid line) is spread out over a broad band, which extends well into the high frequencies, while that of dark vergence (dashed line) is confined to a narrow, low frequency band. Dark accommodation is generally more noisy than dark vergence, but both spectra peak in the same region (between 0.19–0.38 Hz). The spectra for dark accommodation are not unlike those that were previously reported for the accommodative response in the light, in which spectral density was found to have peaks in two loci: in a broad band below 0.5 Hz and in a narrow band around 2 Hz. Similarly, the spectra for dark vergence resemble those reported by Wilson for the open loop vergence response in light.

A statistical cross-correlation analysis revealed the frequency at which dark accommodation was most correlated with dark vergence and the phase relationship between the two waveforms at that frequency (Table 1). A positive phase angle indicates that vergence was leading, and a negative phase angle suggests that accommodation was leading. Both the intrasubject and intersubject variability of the cross-correlation frequency was small (it should be noted that 0.19 and 0.38 Hz were adjacent frequencies on the Fourier frequency spectrum). In contrast, the phase relationship between the two waveforms at the cross-correlation frequency was variable, but in most cases accommodation trailed vergence, as though the low frequency, open loop vergence fluctuations stimulated a concomitant accommodative response through vergence accommodation. The one exception to this was subject 5, for whom accommodation led vergence in two out of three trials.

Discussion

The dark dissociation of accommodation from vergence is interpreted to mean that, in the absence of visual stimulation, accommodation and vergence assume independent resting states and that there is little cross interaction between processes that determine dark vergence and dark accommodation. Figure 4 illustrates a model of vergence and accommodation in which tonic adapters (slow neural integrators) could determine the resting states of accommodation and vergence without causing correlated activity between the two motor systems. Cross-link interactions, known as accommodative vergence and vergence accommodation, are shown to originate from optical reflex accommodation and disparity vergence (fast neural integrators). These fast controllers are followed by tonic adapters located after the cross-link interactions. The tonic adapters, that are responsible for prism adaptation and accommodative spasm, are thought to be the sources of uncorrelated variations of accommodation and vergence when they relax in darkness.

The results of the current study provide information about the location of cross-links between accommodation and vergence. In darkness, neither system is provided feedback, such that variations in tonic accommodation, which occur downstream from the AC/A crosslink, are unable to influence vergence, and vari-
Fig. 3. The Fourier power spectra of dark accommodation and dark vergence of four subjects. Equivalent scales for accommodation and vergence have been used to facilitate direct comparisons (1 D of accommodation = 1 meter angle of vergence). For each patient, the power has been normalized to the highest peak. A through D show subjects 1, 3, 4, 5 respectively.

Table 1. A cross-correlation between the fluctuations between accommodation and vergence in the dark. The temporal frequency at which accommodation and vergence were most correlated in the dark is given as the “cross-correlation frequency.” A positive phase angle indicates that vergence was leading, and a negative phase angle indicates that accommodation was leading.

<table>
<thead>
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<th>Subject</th>
<th>Cross-correlation frequency (Hz)</th>
<th>Phase angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.19</td>
<td>+95</td>
</tr>
<tr>
<td>3</td>
<td>0.19</td>
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</tr>
<tr>
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<td>+98</td>
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</tr>
<tr>
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<td>0.19</td>
<td>-40</td>
</tr>
<tr>
<td>5</td>
<td>0.19</td>
<td>-28</td>
</tr>
<tr>
<td>1</td>
<td>0.38</td>
<td>+25</td>
</tr>
</tbody>
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The correlation between the noise spectra of dark accommodation and dark vergence in the moderate frequency range of 0.19–0.38 Hz (Fig. 3) is interpreted...
Fig. 4. A block diagram illustrating the proposed locations of the tonic controllers (slow neural integrators) of accommodation and vergence with respect to the crosslinks. The input to the tonic integrator for accommodation is the output of the fast neural integrator for accommodation (reflex accommodation) and the CA/C crosslink. The input to the tonic integrator for vergence is the output of the fast neural integrator for vergence (fusional vergence) and the AC/A crosslink. The junction points of the crosslinks have been modeled by Schor and Kotulak in a study of the dynamic interactions between accommodation and vergence.25

to mean that, despite the dissociation of the tonic controllers, some crosstalk between the two systems persists in the dark. The presence of crosstalk in the dark suggests that the source of the low frequency noise is upstream from the crossover points. And since in most cases vergence leads accommodation (Table 1), it is likely that the low frequency noise first enters the feedforward loop of vergence and that it is then transmitted to the accommodative loop via the CA/C crosslink (Fig. 4). The range of phase angles between accommodation and vergence at the cross-correlation frequency (Table 1) could be due to the summation of the output of the slow neural integrator with the signal coming along the direct, parallel, feedforward loop. The frequency of the signal will be unaffected by the summation, but the integrator will introduce a phase lag. The magnitude of this phase lag will depend on the time constant and gain of the neural integrator, parameters which may demonstrate both intrasubject and intersubject variability. It is also possible that correlated variations of dark vergence and dark accommodation do not arise from crosslink interactions. Correlation does not prove causation, and the similar temporal frequency variations of accommodation and vergence in darkness could be due to time variations of noninteracting components between the two motor systems.

If the source of crosslink interactions between accommodation and vergence were the fast neural integrators, and if these interactions occurred in darkness, then one might expect more dark interaction at higher temporal frequencies than at the moderate frequencies where the correlation was found. However, there are two hypotheses that would explain the absence of high frequency crosstalk. The first is that the neural pathway for accommodative vergence is lowpass and the second is that the high frequency noise enters the feedforward loop of accommodation downstream of the AC/A crosslink (Fig. 4). The former hypothesis was proposed by Wilson23 to explain the absence of high frequency noise in the open loop vergence response in the light.

The heterogeneity of the time courses of the dark decay of accommodation and vergence (Fig. 2) has its origin in two sources. The first is the distance between the initial and the final levels of accommodation and vergence, ie, all other things being equal, the greater the distance to be travelled, the greater the time required for decay. Secondly, the decay time constants of each tonic controller will depend on their states of adaptation. This latter effect has been demonstrated for accommodation by Schor, Johnson, and Post23 and for vergence by Schor.24 Both factors, distance and state of adaptation, lend themselves to experimental control; therefore, a further test of the model in Figure 425 would be an experiment in which distance and adaptation were systematically varied so as to change the time courses of the dark decay of accommodation and vergence in a predictable manner.

Key words: accommodation, vergence, dark dissociation, Fourier analysis, cross-correlation analysis

Acknowledgment

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References