Objective Concurrent Measures of Open-Loop Accommodation and Vergence Under Photopic Conditions

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**Purpose.** To investigate the relationship between photopic open-loop accommodation and vergence and the effect of mental effort on these positions.

**Methods.** Twenty subjects (11 men and 9 women) viewed monocularly a photopic (25 cd/m²), high-contrast (90%) Maltese cross-target for 3 minutes, through a 0.5-mm pinhole drilled into an infrared filter. Accommodation was measured objectively at 1-second intervals using a Canon Autoref R-1 infrared optometer, and vergence was recorded continuously and objectively using a differential infrared eye tracking system.

**Results.** Under passive viewing conditions there was a significant correlation between photopic open-loop accommodation and vergence (R = 0.671, P = 0.0012); for the majority of subjects the imposition of mental effort shifted the passive levels of both open-loop accommodation and vergence, but these shifts were unsystematic and uncorrelated (R = 0.259, P = 0.270). The active open-loop positions of accommodation and vergence were also found to be correlated (R = 0.692, P = 0.0007).

**Conclusions.** The influence of proximal stimuli can explain the correlations identified between photopic open-loop positions of accommodation and vergence. The uncorrelated responses of the accommodation and vergence systems to mental effort are likely to reflect interactions between various spatiotopic stimuli including mental effort and perceived proximity. Invest Ophthalmol Vis Sci. 1993;34:2996–3003.

The complex task of maintaining a clear and single binocular image of an object is accomplished by the accommodation and vergence systems, which operate within negative feedback loops to minimize blur and disparity of the retinal image.¹

Under normal viewing conditions, synkinetic interactions between the two systems exist in the form of accommodative vergence, wherein blur-driven accommodation produces a vergence response (defined as the AC/A ratio) and vergence accommodation, wherein disparity-driven vergence produces an accommodation response (defined as the CA/C ratio).¹⁻³ In the absence of visual stimuli, the accommodation and vergence systems are found to adopt stable, intermediate resting positions that range between 0.5 and 1.5 diopters for accommodation and between 0.5 and 0.9 metre-angles (MA) for vergence.⁴⁻⁷ The terms tonic accommodation and tonic vergence were proposed because it was believed that the positions adopted by the two systems while under open-loop conditions reflected a "baseline" level of resting activity or tonus.⁸ There are various methods that can be used to place the accommodation and vergence systems under open-loop conditions, the most frequently used method being darkness. In the current study the accommodation and vergence loops are opened using monocular occlusion and a pinhole pupil under photopic conditions. To distinguish between photopic open-loop conditions and dark-room conditions the following abbreviations will be used; DA and DV for dark accommodation and dark vergence, respectively,⁹ and POA and POV for photopic open-loop accommodation and photopic open-loop vergence, respectively.

**DARK ACCOMMODATION AND DARK VERGENCE**

Various laboratories have reported nonsignificant correlations between DA and DV using a variety of
measurement techniques usually requiring subjective input from the observer, for example, laser optometer, vernier optometer, and a dual-haploscopic optometer to measure DA and nonius alignment and a dual-haploscopic optometer to measure DV. In other investigations nonsignificant correlations have been found between DA and DV using objective techniques, for example, photographic methods to measure both DA and DV, and one study that employed an infrared eyetracker to measure DV while using a laser optometer to measure DA. Significant correlations have been reported by other laboratories using a laser optometer to measure DA and nonius alignment to measure DV, using a dual-haploscopic optometer, and using a vernier optometer and nonius alignment to measure DA and DV, respectively. Results obtained using similar experimental apparatus have been contradictory. For example, no significant correlation between DA and DV was found using a dual haploscopic optometer, which measures accommodative state using the principle of stigmatoscopy and vergence position by subjective alignment of targets presented haploscopically in the two arms of the optometer. Another study by Wolf et al again using a haploscope-optometer found a significant correlation between DA and DV, which measures accommodative state using similar experimental apparatus, and concluded that voluntary mental effort stimulated a "mental slate" or specific task distance inferred by mental imagery, which for their study would be placed at 1.61 D.

Recent studies have demonstrated the potency of proximal stimuli on the open-loop responses of accommodation and vergence. A change in target distance from 0.2 to 3.0 D was found to cause a mean change in the open-loop accommodation response of 1.70 D, which the authors ascribed to proximally induced accommodation. Proximal stimuli have also been shown to influence the open-loop vergence position, changes of 0.37 MA for each MA change in target distance being reported although it has also been indicated that under certain experimental conditions proximal stimuli can produce approximately 70% of the required vergence response. It has been shown that even prior knowledge of surround propinquity (i.e., nearness) can significantly influence open-loop measures of accommodation.

The effect of mental effort on the vergence system is less well established although it is known that voluntary mental effort can be used as a stimulus to both accommodation and vergence. McLin and Schor have examined the open-loop accommodation and vergence response to voluntary mental effort (i.e., "thinking near" or "thinking far") in the light using monocular occlusion and a pinhole pupil. They found that both oculomotor systems responded to voluntary stimuli in a ratio that is very similar to the AC/A ratio, and concluded that voluntary mental effort stimulated accommodation directly with changes in vergence occurring via the accommodative-vergence cross-link.

Recent investigations have led to the proposal that negative feedback models of oculomotor control respond to two distinct classes of stimuli: spatiotopic stimuli (e.g., size change), which induce relatively large, coarse but primary responses; and retinotopic stimuli (e.g., retinal blur and image disparity), which refine these initial responses. It is of considerable interest to examine the responses of the accommodation and vergence systems to purely spatiotopic stimuli. Previous studies that have attempted to examine the effect of spatiotopic stimuli (e.g., voluntary mental
effort) on POA and POV have tended to use small subject numbers because of the complex nature of the measurements.

Photopic Open-Loop Accommodation and Vergence

The accommodation loop can be opened under photopic conditions using a variety of techniques such as, bright empty fields, Maxwellian view, Difference of Gaussians, and when measured under these conditions POA is found to be more proximal than DA. Open-loop vergence can also be measured under photopic conditions by opening the vergence loop using monocular occlusion and a pinhole pupil, and POV has been found to be more divergent than DV. Simultaneous, objective measures of POA and POV have previously been made on a small number of subjects (N = 8 and 5), although the authors did not indicate if any relationship existed between the two systems.

The current study examines objectively and concurrently open-loop accommodation and vergence in 20 subjects viewing a photopic target, using a pinhole pupil to open the accommodative loop and monocular occlusion to open the vergence loop. Measurement of the two open-loop positions using objective techniques avoids any shifts in open-loop accommodation and vergence associated with the mental effort due to subjective judgments. The aim of the experiment was to examine the distribution of and the relationship between open-loop accommodation and vergence under photopic conditions and further to examine the effect of a spatiotopic stimulus (i.e., mental effort) on POA and POV.

MATERIALS AND METHODS

Subjects

Twenty emmetropic visually normal subjects (11 men and 9 women, mean age of 24.2 years, range 19–29 years) took part in the study. All were students in the Department of Vision Sciences at Glasgow Caledonian University and all gave informed consent to take part in the study after the nature of the procedures had been fully explained to them. All procedures were subject to the principles outlined in the Declaration of Helsinki. A full optometric examination was carried out on all the subjects to ensure normal binocular, refractive, and ocular health status. The subjects had best sphere refractive errors between plano and + 0.50 D with no more than 0.50 D of astigmatism.

Apparatus

Accommodation was measured using a Canon Autoref R-1 infrared objective optometer (Canon Europa, The Netherlands), in its single-shot mode of recording. The autorefractor operates on the principle of grating focus and determines the position of focus in three meridians. From this the sphero-cylindrical refractive error can be computed to an accuracy of ± 0.12 D once per second. The reliability and validity of the optometer has been established previously and, it has been used successfully for the measurement of static accommodation under a variety of experimental conditions in numerous research laboratories.

A differential infrared limbal eyetracker mounted on a standard ophthalmic trial frame was used to monitor eye position objectively and continuously. A pair of infrared emitter/detectors are positioned so that when the observer looks at infinity the infrared beam falls centrally on both the nasal and temporal limbal junctions. The outputs from the nasal and temporal detectors are fed into a differential amplifier that produces an output voltage proportional to the amplitude of horizontal eye movements. The infrared sources are chopped at a very high frequency (> 1000 Hz) and the detectors set to recognize only the chopped frequency, which avoids direct current drift and reduces the effect of 1/f noise and any noise from extraneous sources (such as cross-talk between the photodiodes and the infrared optometer). The instrument was found to have a noise level and resolution for horizontal eye movements of 10 minutes of arc under the current experimental conditions. The cross-axis sensitivity was found to be 12 ± 2%, which is very similar to values quoted for other instruments.

Heterophoria measurement using Maddox rod revealed no vertical heterophoria in any of the subjects, and as movement of the fixating eye would be minimal, the problem of horizontal/vertical cross-talk will arise only if the covered eye showed very large vertical eye movements (> 20°) in response to the mental effort task. The signals from the right and left eyes were fed into a Gould 1604 digital oscilloscope (Gould Electronics, UK) interfaced with a computer (Epson PC-XT [Seiko-Epson Corporation, Japan]). This allowed the traces to be viewed in real time and ensured that data-containing artifacts (e.g., blinks) would be eliminated.

Procedure

On entering the laboratory there was no attempt made to disguise the position of either the apparatus, the stimulus, or the relative dimensions of the room. The subjects were therefore fully aware of the position of the target and instrumentation, although all subjects were ignorant as to the aim of the experiment. The subjects were first asked to sit in the dark to allow the dissipation of any transient changes in the tonic positions due to previous near work. A calibration run was first collected for the eyetracker with the subject viewing a scale of 1° steps at 1 m. Saccadic eye movements of varying step sizes were recorded for a range of ± 10°. The output voltage from the eyetracker was...
Photopic Open-Loop Accommodation and Vergence

A high contrast (90%) photopic (25 cd m⁻²) Maltese cross was placed at 0 D vergence in a 5 D Badal stimulus optometer and viewed monocularly through a 0.5-mm pinhole drilled into infrared filter. It has previously been shown that a 0.5-mm pinhole will fully open the accommodative loop. During the experiment the target was viewed through a circular aperture restricting the field of view through the Badal lens to approximately the size of a 35-mm slide, although the angular subtense of the target when viewed through the artificial pupil was 2.39°; the ambient room illumination was constant at approximately 250 lux.

Baseline measurements of open-loop accommodation and vergence were then taken for a period of 1 minute while the subjects viewed the Maltese cross target monocularly under photopic conditions through the pinhole pupil. During this period 30 static measures of the accommodation response were obtained, and 5 continuous measures of the right and left eye position each of 10 seconds duration were collected at a sampling frequency of 102.4 Hz. The continuous signals were stored initially in the oscilloscope and then transferred to an IBM-compatible computer (Epson PCE-XT) for subsequent analysis using Asystant (Asyst Software Technologies) software. The subjects were then required to perform a mental arithmetic task that consisted of counting backward in sevens to themselves from a three-digit number set by the examiner for a period of 3 minutes and further measures of accommodation and eye position signals were recorded. Such a task was previously used to induce a level of mental activity that is relatively difficult but remote from the target viewed by the subject, in contrast to tasks (e.g., to identify a particular feature of the target) that initiate mental activity directly related to the stimulus.

**RESULTS**

**Passive Measures of POA and POV**

A significant correlation (Fig. 1, \( y = -0.65 + 0.90x \), \( R = 0.671, F = 14.705, df = 19, P = 0.0012 \)) was found between the passive viewing positions of POA and POV. The mean passive POA position was found to be 1.25 ± 0.72 D (Table 1), a value similar to previous reports of POA measured using the Canon optometer. The mean passive POV was found to be 0.48 ± 0.97 MA (Table 1), which is more divergent than previous reports of DV. This is also relatively more divergent than the mean open-loop position of accommodation by approximately 0.65 MA. An examination of the regression shows that for 0 D of POA, subjects will exhibit approximately 0.65 MA of divergence. It can also be seen that several subjects exhibit divergent POV positions under the conditions of the current study. The slope of the regression is very close to unity at 0.90 indicating an almost one-to-one relationship between POA and POV.

**The Effect of Mental Effort on POA and POV**

Both positive and negative shifts in accommodation and vergence resulted from the mental arithmetic task (Fig. 2). Linear regression of the mentally induced shift in POA against the mentally induced shift in POV revealed no significant relationship (Fig. 2, \( y = -0.04 + 0.39x, R = 0.26, F = 1.296, df = 19, P = 0.270 \)). It can be seen from the figure that the direction of the mentally induced shift is often of opposite sign in the

**TABLE 1. Mean (± SD) Values (N = 20) of Passive and Within-Task Open-Loop Measures of accommodation and Vergence**

<table>
<thead>
<tr>
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<th>Mean Passive</th>
<th>Mean Within-Task</th>
<th>Shift</th>
<th>Significance</th>
</tr>
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<tbody>
<tr>
<td>POA (D)</td>
<td>1.25 (0.72)</td>
<td>1.41 (0.75)</td>
<td>+0.16</td>
<td>( t = 1.241, df = 38, P &gt; 0.10 )</td>
</tr>
<tr>
<td>POV (MA)</td>
<td>0.48 (0.97)</td>
<td>0.54 (1.47)</td>
<td>+0.06</td>
<td>( t = 0.341, df = 38, P &gt; 0.10 )</td>
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POA = photopic open-loop accommodation; POV = photopic open-loop vergence; D = diopters; MA = metre-angles.
Accommodation shift (D)

FIGURE 2. Relationship between the induced shifts in open-loop accommodation and vergence showed no significant regression \((P = 0.183)\). Typical standard deviations were \(\pm 0.25\) D for the accommodation measures and \(\pm 0.25\) MA for the vergence measures.

two systems; with positive changes in accommodation often being accompanied by negative changes in the vergence system and vice-versa. This finding describes clearly the disparate and uncorrelated responses of the accommodation and vergence systems to the mental effort task.

Table 1 shows the mean pretask and within-task positions of POA and POV and the mean shifts found in both systems as a result of the mental effort task. The mean shift in the accommodation system was \(+0.16\) D, which was not significant (paired \(t\) test, \(t = 1.241, 38\) df, \(P > 0.10\)). Regression of the pretask and within-task measures of accommodation revealed a significant relationship (Fig. 3A, \(y = 0.49 + 0.73x, R = 0.706, F = 17.874, df = 19, P = 0.0005\)). The slope of the relationship being flatter than unity (0.73) indicates that the within-task positions of POA were not quite as widely distributed as the original passive positions of POA.

The mean mentally-induced shift in the vergence system was \(+0.06\) MA, and this difference between pretask and within-task POV positions was not significant (paired \(t\)-test, \(t = 0.341, 38\) df, \(P > 0.10\)). Regression of the within-task POV position against the passive POV position revealed a significant relationship (Fig. 3B, \(y = -0.09 + 1.31, R = 0.87, F = 56.389, df = 19, P = 0.0001\)), in this case the gradient was greater than unity (1.31) indicating that the task-induced POV positions tended to have a wider distribution of values compared with the passive POV positions.

Regression of the within-task measures of POA and POV was significant (Fig. 4, \(y = -1.37 + 1.36x, R = 0.69, F = 16.514, df = 19, P = 0.0007\)). It can be seen that the slope of the regression is now greater than unity (1.36) compared to the slope (0.90) of passive POV against passive POA (Fig. 1). The increased slope of the regression can be attributed to both a narrower distribution of within-task POA values (Fig. 3A) and a wider distribution of within-task POV values (Fig. 3B) as a result of the mental effort task.

DISCUSSION

Passive Measures of POA and POV

The values of passive POA and passive POV reported in this study agree with previously reported values of open-loop accommodation\(^{25,26,36}\) and vergence\(^{37}\) mea-

FIGURE 3. (a) Relationship between pretask and within-task measures of photopic open-loop accommodation showed a significant regression \((P = 0.0005)\). Typical standard deviations were \(\pm 0.25\) D. (b) Relationship between pretask and within-task measures of photopic open-loop vergence showed a significant regression \((P = 0.0001)\). Typical standard deviations were \(\pm 0.25\) MA.
found that the POV positions for four of five subjects
method similar to that used in the current study. They
darkness and under photopic conditions using a
sured under photopic conditions. Previous reports of
POA and DA. A recent study measured DV and dis-
howevers measured tonic accommodation and tonic vergence in
darkness and under photopic conditions using a
method similar to that used in the current study. They
found that the POA positions for four of five subjects
tended to be more divergent than DV by up to 2 MA,
although they could identify no difference between
the vergence loop is opened under photopic condi-
tions.
The Effect of Mental Effort on POA and POV
The effect of the mental arithmetic task on the accom-
modation and vergence systems appears to be unpre-
dictable and indeterminate. Indeed it can be seen
from Figure 2 that the direction of change was often
opposite in the two systems with negative shifts in ac-
commodation accompanying positive vergence shifts
and vice-versa. This lack of correspondence between
the mentally induced shifts in accommodation and
vergence is puzzling because mental effort is likely to
represent a common spatiotopic input to both accom-
modation and vergence systems due to a subject’s awareness
of the target location and the influence of the room
dimensions. The drive to accommodation and ver-
gence resulting from these proximal stimuli would be
expected to be similar and it may be the responses to
these proximal stimuli that underly the correlation be-
tween passive POA and POV found in the current
study.

FIGURE 4. Relationship between the within-task measures of
open-loop accommodation and vergence showed a signifi-
cant regression ($P = 0.0007$) Typical standard deviations
were $\pm 0.25$ D for the accommodation measures and $\pm 0.25$
MA for the vergence measures.

The correlation between passive POA and POV
measurements agrees with similar results reported for
DA and DV. The effect of proximal stimuli on
open-loop measures of accommodation and vergence is
now well established. A recent review discussed
the difficulty in obtaining veridical measures of open-
loop accommodation and vergence regardless of the
method used to open the feedback loops. The photo-
ic measures of open-loop accommodation and ver-
geence collected in the current study are likely to have
been significantly influenced by such factors as per-
ceived proximity and surround propinquity, as there
was no attempt made to disguise the room dimensions
and surroundings or the position of the target relative
to the observer. All these influences could have a
proximal effect on the open-loop positions measured.
Even factors such as the room surroundings have been
shown to significantly influence open-loop measures of
accommodation. Under the current experimental
conditions there is likely to have been a strong target-
dependent proximal response in both the accommoda-
tion and vergence systems due to a subject’s awareness
of the target location and the influence of the room
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geence resulting from these proximal stimuli would be
expected to be similar and it may be the responses to
these proximal stimuli that underly the correlation be-
tween passive POA and POV found in the current
study.
cluding both perceived proximity and mental effort. Thus it appears that while the mental effort stimulus is strong enough to modify the passive positions of POA and POV, the proximal stimulus ensures that correlation between the accommodation and vergence systems is maintained.

The occurrence of negative oculomotor shifts in response to the mental arithmetic task can also be explained by the combined effect of these spatiotopic stimuli and therefore will depend on the position at which a particular person perceives the mental effort task to be, such visual imagery has previously been noted to influence DA. If a particular subject imagines the mental effort task to be more distant than the position resulting from the various proximal stimuli then a negative shift of accommodation or vergence may occur. However, the occurrence of opposing shifts in the two systems is puzzling and deserves further investigation.

**Key Words**

accommodation, vergence, open-loop, photopic, mental effort

**Acknowledgment**

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