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Accommodation microfluctuations and pupil size during sustained viewing of visual display terminals

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Summary

Accommodation microfluctuations comprise two dominant frequencies; a low frequency component (LFC $\leqslant$ 0.6 Hz) and a high frequency component (1.0 Hz < HFC < 2.1 Hz). In the present experiment we examine accommodation microfluctuations and steady-state pupil responses during sustained viewing of visual display terminals (VDTs). Steady-state accommodation and pupil responses were measured continuously and simultaneously using a modified Canon Autoref R-1 infra-red objective optometer and an Hamamatsu C3160 Perceptscope Video Area Analyser. Measurements were obtained at three time intervals (0, 10 and 20 min) during a 20 min reading task presented on five different displays. With the displays placed at 50 cm, the task was to locate and identify typographical errors in one of five sets of standard text. Five young visually-normal emmetropic subjects with a mean age of 22.5 ± 3.0 years participated in the study. Two-way ANOVA revealed no significant variation in the magnitude of the accommodation microfluctuations with either display or task duration, nor was there any significant interaction between these two factors. There was no significant variation in mean pupil diameter with either display or task duration. These measures may have the potential to provide objective information about visual display quality. © 1999 The College of Optometrists. Published by Elsevier Science Ltd. All rights reserved

Introduction

Although visual fatigue is experienced by some observers when they perform prolonged near visual tasks, the physiological basis for this fatigue remains unclear (Campbell and Durden, 1983; Goussard *et al*., 1987; Burns, 1998). Various measures of visual function have been employed in an attempt to find an index of visual fatigue and the occurrence of symptoms such as transient blur and diplopia have lead to investigation of oculomotor functions in response to near work. Measures of fixation disparity (Sheedy and Saladin, 1983; Jaschinski-Kruza and Schubert-Alshuth, 1992; Jaschinski-Kruza, 1993), accommodation (Östberg, 1980; Owens and Wolf-Kelly, 1987; Jaschinski-Kruza, 1991; Jaschinski-Kruza and Schubert-Alshuth, 1992; Jaschinski *et al*., 1996) and vergence (Owens and Wolf-Kelly, 1987; Tyrrell and Liebowitz, 1990; Jaschinski-Kruza, 1991; Jaschinski *et al*., 1996) have been made before and after near work using both VDTs and hard copy, although the results have been inconclusive. Those studies which used both VDTs and hard copy could find no differences between the two conditions, and often the subjective and objective measures of visual fatigue were found to be weakly correlated (Owens and Wolf-Kelly, 1987; Burns, 1998). Additionally, those studies which used severe viewing conditions to induce changes in oculomotor function, with the task being placed at 20 cm (i.e., an accommodative demand of 5 D) are not typical of VDT use, during which the screen tends to be located at a distance of 50 cm or greater (Jaschinski-Kruza, 1990, 1991). More recently studies have been conducted using the static accommodation response as an objec-

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tive measure of visual performance while viewing VDTs under degraded stimulus conditions such as increased screen reflection (Collins *et al*., 1994) and the presence of flicker (Chauhan and Charman, 1996).

The continuous accommodation response to a static near target exhibits small temporal variations in power termed microfluctuations (Collins, 1937; Campbell *et al*., 1959). Two dominant regions of activity can be identified within the waveform of these microfluctuations; a low frequency component (LFC) of less than 0.6 Hz, and an high frequency component (HFC) which occurs between 1.0 and 2.3 Hz (Campbell *et al*., 1959; Charman and Heron, 1988; Winn and Gilmartin, 1992). It appears that the microfluctuations represent a combination of "plant noise" and neurological control; the former being attributed to the effects of respiration (Collins *et al*., 1995) and arterial pulse (Winn *et al*., 1990; Collins *et al*., 1995), the latter to the LFC (Winn and Gilmartin, 1992). There is evidence supporting the possible role of the LFC in the neurological control of steady-state accommodation; when the ocular depth-of-focus is increased by the use of a small artificial pupils (Campbell *et al*., 1959; Gray *et al*., 1993a) or by reductions in target luminance (Gray *et al*., 1993b) the power in the LFC is correspondingly found to increase.

An examination of microfluctuations may therefore provide information regarding the accuracy of the negative feedback control system of the steady-state accommodation response to any stimuli including VDTs. A previous study identified increases in the power of the microfluctuations (between 0 and 1.5 Hz) as a consequence of viewing VDTs (Iwasaki and Kurimoto, 1987). The range of frequencies chosen in this study, however, clearly does not allow differentiation between the LFC and HFC identified by other authors (Campbell *et al*., 1959; Charman and Heron, 1988; Winn and Gilmartin, 1992).

The pupil is known to be constantly active even under steady-state luminance conditions (Alexandridis, 1985) and it has been suggested that variations in pupil instability may be related to the level of fatigue experienced by the subject (Geacintov and Peavler, 1974; Goldwater, 1974; Ukai *et al*., 1997). Previous experiments have found that under certain conditions the pupil fails to redilate following a concentrated near vision task even though a substantial reduction in accommodation may have occurred (Gilmartin *et al*., 1990), suggesting the possibility of pupil after-effects following near work. Tsuchiya *et al*. (1989) found that these pupil "after-effects" occurred even in the absence of changes in the tonic level of accommodation and they propose the possibility that pupil changes may provide a method of monitoring the effects of sustained near vision, although they employed unusually high accommodative stimulus demands to cause changes in the pupil diameter ($\sim$10 D). Recently an increased incidence of pupillary hippus was found in VDT users, using a similar experimental protocol (Ukai *et al*., 1997).

An examination of continuous accommodation and pupil responses has the potential to provide an index of visual performance during sustained near vision of a variety of targets including VDTs. We have developed a system which allows continuous accommodation and pupil responses to be measured simultaneously.

In the present study continuous recordings of accommodation microfluctuations and horizontal pupil diameter were measured simultaneously while the subjects performed a 20 min near vision task using 5 different displays (4 types of VDT and hard copy). The aims of the study were:

(a) to establish whether these measures could be successfully obtained when viewing naturalistic stimuli,
(b) to examine the steady-state variations of the accommodation and pupillary systems during prolonged near vision with a variety of displays.

Methods

Accommodative microfluctuations were measured with a specially modified Canon Autoref R-1 infra-red objective optometer which can be used in continuous or single shot mode. In normal operation the optometer uses the principle of grating focus to drive a lens along a carriage until the output voltage is at a maximum, and computes the time taken to reach this point. It has three sets of detectors in three different meridians and from these values it calculates a spherocylindrical value of the eyes refractive power to $\pm$0.12 D. In continuous recording mode the lens carriage is disabled and set manually to allow the voltage output from either of the three detectors to be sampled continuously. The modification and operation of the present optometer for use in continuous mode are described fully elsewhere (Pugh and Winn, 1988, 1989), but other modifications have been described (Davis *et al*., 1993; Wetzel *et al*., 1996). This system has been successfully used for the continuous recording of accommodation in several previous studies (Winn *et al*., 1990; Gray *et al*., 1993a,b).

The optometer has open-field presentation via a semi-silvered mirror, which allows the target to be placed directly in front of the observer anywhere within an 18×50 degree field of view, and provides observation conditions which closely approximate normal visual environments.

Horizontal pupil diameter was measured using a Hamamatsu C3160 Perceptscope Video Area Analyser (Hamamatsu, Japan). The instrument analyses the size of images from the video camera of the Canon R-1 optometer, and has a resolution of 0.04 mm under these conditions.

The outputs from the optometer and the video area analyser were fed into a digital storage oscilloscope (Gould 1604) which was connected to an on-line computer (Epson PCe-XT) through an IEEE-488 interface. This arrangement allows the traces to be viewed during the experiment and any data containing artefacts due to blinks or eye movements to be identified.

Five young emmetropic subjects (one male/four female) were used with a mean (±standard deviation) age of 22.5 ± 3.0 years. The subjects all had normal visual function as measured by standard clinical optometric tests (visual acuity, ocular muscle balance, amplitude of accommodation). All subjects were familiar with VDTs and used them to varying extents during the day. None had previously reported asthenopic symptoms in response to VDT use. Five displays were presented to each subject as follows; hard copy (HC), cathode ray tube (CRT), electroluminescent panel (EP), gas plasma display (GP) and liquid crystal display (LCD)(see *Table 1*). Each display was aligned along the primary visual axis to ensure that the eyes were neither continuously elevated nor depressed during the task. The task in all conditions was to locate and identify all typographical errors present in one of five sets of text. Each set had the same number of errors, on average five per page (minimum 4, maximum 6). The sets of text and the displays were randomised so that by the end of the experiment each subject had seen all text sets and all displays. The task distance was 50 cm which was felt to be more typical of normal VDT use (Jaschinski-Kruza, 1990, 1991) and display luminances ranged from 20 to 35 cdm^{-2}. Each display was presented on a featureless background and the ambient background luminance was $\sim$250 cdm^{-2}. All luminances were measured using a digital spot photometer (*Minolta Luminance Meter LS 110*) whose response is designed to match closely the CIE Relative Photopic Luminosity Response.

Before the subject began the task three continuous recordings of accommodation each of 10 s duration were taken. The subjects then read the complete text for 20 min and a further three continuous recordings of accommodation were taken after 10 min and at the conclusion of the 20 min period. Static measures of the accommodation response were taken at the beginning and end of the 20 min task.

The continuous recordings of accommodation and pupil diameter were collected at a sampling rate of 102.4 Hz and were then smoothed with a high frequency cut at 10 Hz and a power spectrum calculated for each trace with a frequency resolution of 0.1 Hz (Pugh *et al.*, 1987). The individual power spectra from each recording condition were then averaged giving a final power spectrum with 6 df. It has been shown the probability density function of any one frequency bin (each of width 0.1 Hz) in a power spectrum obtained by a single Fourier transform is that of a chi-squared distribution of order 2. For such a distribution the standard deviation is equal to the mean value. By averaging more power spectra the confidence in the distribution increases and the standard deviation correspondingly decreases and becomes equal to $\sqrt{(2/2m)} \times$ mean value in each frequency bin (where m = number of spectra). If the average value of multiple frequency bins is taken the confidence increases further and the standard deviation then becomes $\sqrt{(2/2mn)} \times$ mean value of all frequency bins averaged (n = number of frequency bins averaged; Pugh *et al.*, 1987).

Results

The root-mean-square (rms) value of the microfluctuations describes the standard deviation of the waveform around the mean accommodative level. No significant variation could be identified in the rms value for the five displays or the three time intervals, nor was there any significant interaction between the variables of display type and sample time (*Table 2*, ANOVA, all $p > 0.10$). The static levels of accommo-

Table 1. Characteristics of the five displays used in the present study. The figure in brackets shows the Snellen equivalent for each character size. This was calculated by measuring the size of the letter and calculating the angular subtense of this size of letter for the task distance (50 cm)

Display	Angular subtense	Character colour	Background colour	Contrast
Cathode ray tube	0.57° (6/36)	White	Black	80%
Electroluminescent	0.34° (6/24)	Yellow	Black	80%
Gas plasma	0.69° (>6/36)	Red	Black	70%
Liquid crystal	0.57° (6/36)	Blue	Grey	70%
Hard copy	0.57° (6/36)	Black	White	90%

Table 2. Mean (±SD) root-mean-square values of accommodation microfluctuations for each display. Units are dioptres

	Time	
Display	0 min	20 min
EP	0.30 ± 0.05	0.31 ± 0.09
CRT	0.24 ± 0.06	0.26 ± 0.09
HC	0.25 ± 0.05	0.25 ± 0.07
GP	0.24 ± 0.07	0.26 ± 0.08
LCD	0.21 ± 0.08	0.23 ± 0.08

dation response are illustrated in *Table 3* and it can be seen that the static accommodation response is accurate for all displays, with a normal lag of accommodation occurring in most cases. There was no significant variation in the static accommodation response with sample time ($p > 0.10$) or display ($p > 0.10$).

For the purposes of this study the LFC was defined as the three frequency bins between 0.3 and 0.6 Hz, as this will avoid including any very low frequency drift in the mean accommodation level (< 0.3 Hz), and also avoids encroaching upon the HFC which has been found to lie above 1.0 Hz (Campbell *et al*., 1959; Winn and Gilmartin, 1992; Gray *et al*., 1993a,b). The HFC is defined as the three frequency bins centred around the peak frequency of this component. The peak frequency was found to vary between individuals (1.1 Hz for observer NP, 1.3 Hz for observers GR, RD and CM and 1.5 Hz for observer JH) although it remained stable in any single observer, a characteristic which has been reported previously (Winn and Gilmartin, 1992). The power in both the LFC and HFC at the beginning and the end of the task period is given in *Table 4*. After 20 min of viewing there are no obvious systematic changes in these components, although increases in the power of the LFC are found for one subject (RD) particularly for the HC and EP displays. There is no systematic variation in the power of the HFC with time.

Table 3. Mean (±SD) accommodation response for each display. Units are dioptres

	Time	
Display	0 min	20 min
EP	1.97 ± 0.09	1.89 ± 0.15
CRT	1.85 ± 0.15	1.79 ± 0.22
HC	1.76 ± 0.10	1.79 ± 0.20
GP	1.79 ± 0.12	1.69 ± 0.05
LCD	1.65 ± 0.12	1.73 ± 0.12

The variation in the mean pupil diameter between different displays only reached significance at the 5% level, as did the variation in pupil diameter with time, but there was no significant interaction between these two factors (*Table 5*, ANOVA; display, $F = 2.873$, df = 4,14, $p = 0.03$; time, $F = 3.471$, df = 2,14, $p = 0.04$; interaction $F = 1.672$, df = 2,14, $p = 0.139$). It can be seen (*Table 5*) that while all the pupil diameters tend to be fairly large, there is a slight tendency for the mean pupil diameter to increase slightly with time. It can also be seen that the mean pupil diameters are smaller for the CRT display than the other four displays.

Discussion

The present study demonstrates the feasibility of measuring accommodation and pupil responses continuously and simultaneously during a sustained near vision task, irrespective of whether this task is presented upon a VDT or in hard copy mode. We have demonstrated that these measurements can provide detailed information about the components of both accommodation and pupillary responses during sustained near vision.

Inspection of the continuous accommodation response reveals changes in the two dominant frequency

Table 4. Mean (±SD) power in the LFC and HFC of the accommodation microfluctuations for each display. Power is measured as the area (D^2) under the mean Fourier transform of the microfluctuations waveform for each increment of frequency (Hz). Units are therefore D^2/Hz

	Time			
	0 min		20 min	
Display	Power in LFC	Power in HFC	Power in LFC	Power in HFC
EP	0.13 ± 0.02	0.20 ± 0.13	0.09 ± 0.07	0.07 ± 0.03
CRT	0.10 ± 0.06	0.22 ± 0.14	0.12 ± 0.06	0.06 ± 0.03
HC	0.11 ± 0.05	–0.08 ± 0.04	0.13 ± 0.09	0.09 ± 0.03
GP	0.14 ± 0.08	0.10 ± 0.03	0.13 ± 0.07	0.09 ± 0.03
LCD	0.06 ± 0.01	0.10 ± 0.03	0.06 ± 0.02	0.06 ± 0.04

Table 5. Mean (±SD) horizontal pupil diameter for each display. Units are millimetres

Display	Time	
	0 min	20 min
EP	5.64 ± 0.43	6.32 ± 0.70
CRT	5.60 ± 0.29	5.47 ± 0.45
HC	6.45 ± 0.56	6.50 ± 0.35
GP	6.03 ± 0.65	6.56 ± 0.54
LCD	6.34 ± 0.65	6.21 ± 0.34

components of the fluctuations with time, particularly for one observer (RD). Increases in the LFC of the microfluctuations after 20 min viewing can be seen for the several of the displays. These subtle changes in the frequency characteristics of the continuous accommodation response are occurring in asymptomatic subjects. It is possible that an examination of the LFC and HFC of the continuous accommodation response in symptomatic subject groups or under sub-optimal viewing conditions may offer a subtle indicator of near visual performance or accuracy.

An examination of the microfluctuations of accommodation could provide information about subtle changes in the accommodation response when the colour saturation of the display is altered, or if isoluminant colours are presented on the display (Lee *et al.*, 1999). In the present study, the exact colour specifications of the monitor and background were not noted, however the GP and LCD displays appeared the most difficult to focus on subjectively. The GP display presents a relatively saturated red figure on a black background while the LCD display presents a subjectively desaturated blue figure on a grey background. Interestingly these displays also had the lowest figure/ground contrast and showed the greatest lags of accommodation, although these lags were not greater than normal. An examination of the microfluctuations could provide extra information about the accommodation response while viewing VDTs under degraded stimulus conditions such as increased screen reflection (Collins *et al.*, 1994) or flicker (Chauhan and Charman, 1996).

The lag of accommodation found for each display was within the range which would be expected using the Canon R-1 optometer under these stimulus conditions. The lag of accommodation is critically dependent upon the ocular depth of focus which is in turn dependent upon several co-varying factors. The first of these is pupil size which in the present study was always large ($\leqslant$5 mm) due to the relatively low levels of illumination. It should be noted that these levels of illumination are still well within the photopic range. This large pupil size would produce a small depth of focus value. The second factor to influence depth of focus would be target size and contrast, depth of focus being greater for larger targets and targets with poorer contrast, and we have noted above that although the lags of accommodation were normal for each display they were greatest for the displays with the poorest contrast.

Our findings demonstrate that continuous accommodation and pupil responses can be measured during sustained near viewing of a variety of targets and may represent a potentially useful method for investigating sustained responses to near visual tasks. The effect of variations in display characteristics such as luminance, colour, contrast, letter size and flicker could be readily assessed using the present technique. It could also be applied to early presbyopic subjects to assess the quality of the accommodation response with different near vision prescriptions, as this has previously been shown to be a factor in reports of asthenopia in presbyopic VDT users (Martin and Dain, 1988; Burns, 1998).

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