Visual strain: a comparison of monitors and head-mounted displays

Frank Kooi
TNO Human Factors Research Institute
P.O. Box 23, 3769 ZG Soesterberg, The Netherlands
Tel. (31).3463.56242
Kooi@tm.tno.nl

ABSTRACT

New methods to measure information uptake and eye strain have been developed. The speed of information uptake is measured with a reading task that demands quick and accurate eyemovements. Accommodative facility is shown to be a good measure for eye strain. A standard monitor and three types of HMD's were compared on both tasks. The HMD's were i) binocular and immersive, ii) monocular and see-through, and iii) monocular and see-around. These HMD types find applications in Virtual Environments, the cockpit, and Soldier Modernization respectively. Reading performance was measured while the subject was stationary and during head motion. From the experimental results rules of thumb for the use and design of HMD's are derived.
Key words: visual strain, head mounted displays, reading rate, eye fatigue, accommodative facility.

1. INTRODUCTION

Visual strain and fatigue are important determinants of functionality and user acceptance of displays. Head Mounted Displays (HMD's) have repeatedly been shown to be potential sources of visual strain[1,2,3]. It is therefore important for both the user and the designer of HMD's to be able to understand and measure visual strain. The goals of the present study are threefold: 1) to develop a technique to quantify the level of eye strain, 2) to develop a technique to quantify visual information uptake, and 3) to compare basic HMD types using these tests. The speed of information uptake is measured with a dynamic reading task that demands quick and accurate eyemovements, as is the case in a visual search task. The level of visual strain was measured by the 'accommodative facility': the ability of the eyes to alter accommodation between near and far. With these techniques the rate of information uptake and the resulting level of visual strain of three types of HMD's were compared to a standard table-top monitor.

2. THE DISPLAY SYSTEMS

2.1 Design considerations

Four display systems were chosen to be representative of four basic configurations. The reference is the standard table-top monitor. One of the HMD's is representative for the virtual environment (VE) market which uses binocular immersive HMD's. The user is immersed in the virtual environment by blocking out the natural field of view. The other two types of HMD's are representative for a "head mounted vision aid" function of a HMD. The user is still able to look around and is provided extra visual information by way of the (inset) HMD image. The user thus is able to simultaneously (see-through) or alternatively (see-around) view both the real world and the displayed image. Such HMD's are planned to be used for the soldier of the future ("Soldier Modernization"), for pilots, and for various kinds of work support.

The first three display systems are equal in spatial resolution (VGA, 640x480) and field of view (23 x 18.5 deg); any difference in task performance between these three systems will therefore not be due to image quality. The binocular HMD made by Virtual io (Virtual io, Seattle, WA, USA) was made monocular by covering up the left image. The monocular "Vision Sport" HMD made by Virtual Vision (Redmond, WA, USA) only displays the image to the right eye and allows a nearly unobstructed view of the world for the left eye.

Table I. Specifications of the four display systems.

		monitor (binocular)	Virtual io binocular HMD	Virtual io monocular HMD	Vision Sport monocular HMD
field of view (FOV)		23° x 18.5°	23° x 18.5°	23° x 18.5°	17.3° horiz.
viewing distance	accommodation	63 cm	4 m	4 m	adjustable
	convergence	63 cm	2.5 m	-	-
resolution		640 x 480	640 x 480	640 x 480	± 160x250
update rate (Hz)		60 Hz	60 Hz	60 Hz	60 Hz
letter luminance		93 cd/m²	38 cd/m²	38 cd/m²	3.9 cd/m²
room luminance		20 cd/m² mean 50 cd/m² max	0 cd/m²	20 cd/m² mean 50 cd/m² max	.2 cd/m² mean .5 cd/m² max
weight		not revelant	296 g	296 g	140 g
see-through		not revelant	0 %	4.4 %	0 %
see-around		not revelant	none	50% (in lower-half of natural FOV)	L eye: 80% R eye: 50%

3. READING TASK

3.1 Design considerations

The performance task was chosen to maximally induce visual strain and to measure the rate of information uptake at several resolution levels. The task was continuous (no rest breaks) and forced the subject to make repeated changes in viewing direction. The dynamic, uninterrupted character of the task maximizes the chance of visual strain. Letters were presented at four sizes, ranging from large to near legibility threshold. This yields a measure of reading rate at four specified resolution levels. The task was performed while sitting still (static) and while moving the head sideways (rotating). The latter condition simulates natural movements which people make while reading or watching TV.

3.2 Stimulus

The subject was presented with a 3x3 letter matrix presented on the screen. The letters were spaced apart by 1x their width, and presented at 4 different sizes, i.e. 1.15 deg, 0.86 deg, 0.56 deg, and 0.29 deg. The smallest letter was 3.3 times larger than the reading threshold. The letters were semi-randomly chosen from the set A, B, C, D, and E. On each presentation the chance that the central letter was an "A" was set at 40%.

A sample letter matrix of the reading task.

A	B	C
C	A	E
B	A	C

3.2.2 Time sequence

The matrix with the largest letters was sequentially positioned at four screen locations: left-top → right-bottom → right-top → left-bottom, separated horizontally and vertically by 7.6 deg. The onset of the next presentation coincided with the offset of the previous one. This design forces the subject to make diagonal and vertical saccades in order to read the central letter. These eye movements maximally stress the extra-ocular eye muscles[4,5]. At 0.45 s after the offset of the last of the four presentations (left-bottom), the same sequence was repeated with the smaller letter size, again starting at the top-left. The delay gave the subject a little break before the next sequence started. The same sequence kept repeating itself for 12 minutes without a break in order to maximally stress the visual system.

3.3 Procedure

The task was to press a keyboard stroke as quickly as possible when the central letter was an "A". The dependent variable in this experiment was the duration the letter matrix stayed on the screen. Each time the central letter (A) was correctly identified, the duration was shortened by 10%; each time the central letter (A) was missed or incorrectly identified, the duration was lengthened by 10%. In this way the maximally attainable reading speed is measured using the so-called staircase method. The response had to be given before the next letter disappeared from the screen. A letter "A" never followed a letter "A" to avoid confusion. The starting duration was 0.4 s (equivalent to 2.5 Hz).

3.4 Experimental design

The sequence of the conditions was balanced according to a digram-balanced Latin square[6], so as to minimize practice effects. Eight (naive) observers participated in the experiment. Each had normal vision as described in section 2. Four subjects did the tests in the morning and the other four in the afternoon. The four display systems described in section 4 were tested under two conditions: stationary and rotating. In the stationary condition the subjects viewed the screen while keeping their head steady. In the rotating condition the subjects slightly rotated their head with a frequency of 0.25 Hz and a ± 15 deg sideways amplitude. These two experimental conditions simulate stationary and moving viewing conditions and were always tested back to back with a 2 minute break. Half of the subjects did the rotating condition first followed by the stationary condition; the other half started with the stationary condition followed by the rotating condition

3.5 Results

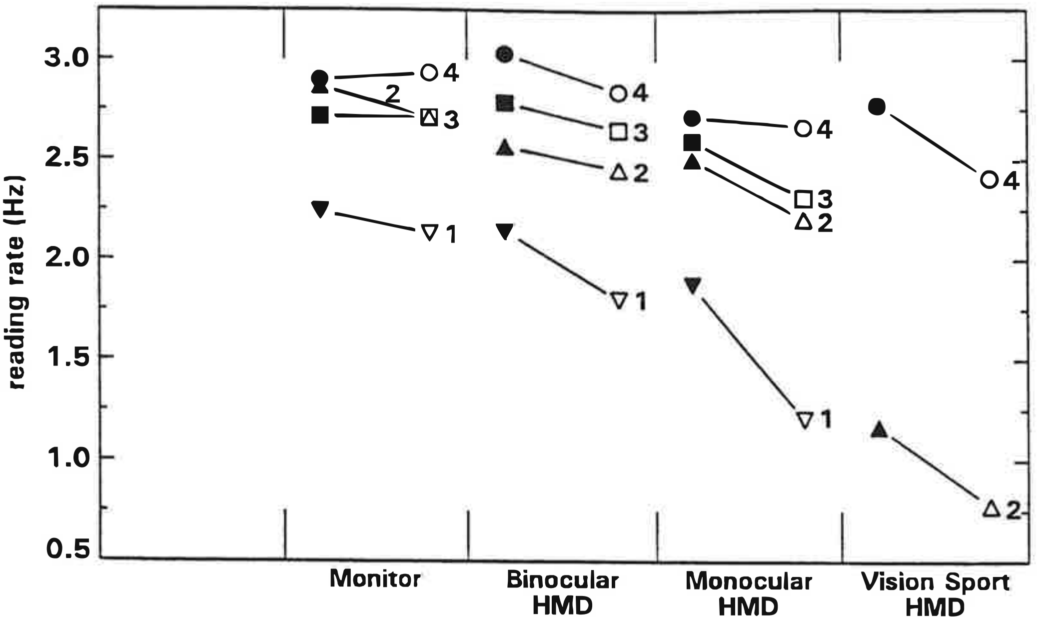
Each condition was tested for 12 minutes. Data analysis indicated that a performance plateau was reached very quickly and that no signs of fatigue within the 12 minute time-span was evident. For this reason the average letter reading frequency of the 12 minute time span is presented. The data is analyzed according to each of the independent variables: male-female, morning-afternoon, chronological order of presentation, stationary-rotating, display system, and letter size. The parameters male-female, morning-afternoon, and chronological order did not have a significant effect on the scores. The absence of an effect of time-of-day and chronological order indicates that (long term) fatigue was not induced by viewing the display systems.

The data as a function of the aforementioned variables (stationary versus rotating, display system, and letter size) are presented in Figure 1, which shows the median reading speed of the 8 subjects.

A comparison of the four display systems shows the monitor and binocular immersive HMD to be best and the two monocular see-around HMD's to be worse. Of the four systems the Vision Sport differs significantly from the other three. The others differ as follows: monitor - monocular HMD, P=0.025, binocular HMD - monocular HMD, P=0.05, and monitor - binocular HMD, P=0.88 (not significant).

The reading rate is higher for larger letters. The largest change occurs between the two smallest sizes 1 and 2.

The static-rotating effect (closed versus open symbols in Fig. 1) depends both on display system and on letter size, but in general the reading rate tends to be lower if the head is moved sideways (rotating). The effect is smallest with the monitor (statistically not significant), and largest with the two monocular see-around HMD's. The reduction in reading rate due to head rotation is greatest with the smallest letter size. Though for the larger letter sizes the reduction in reading speed is still evident in Figure 1, each individual reduction is not statistically significant (Table III). An interpretation of these results is given in the discussion.



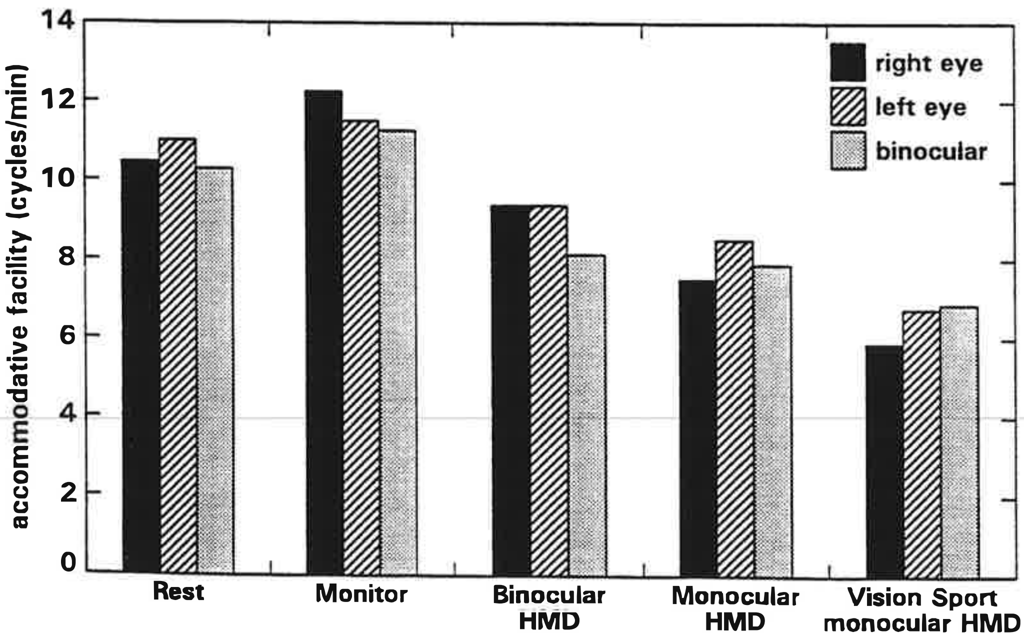


Figure 1 (top). Comparison of reading performance (median of subjects) for the various experimental conditions and display systems. The filled and open symbols refer to the stationary and rotating condition respectively. The numbers 1-4 refer to the letter size. Reading rate is higher with larger letters and for the head-stationary condition.

Figure 2 (bottom). Comparison of visual strain as measured by accommodative facility for the four display systems. Accommodative facility is the number of times within a minute that fixation can be switched between near and far. Results are shown for the binocular and both monocular conditions.

Table III. Levels of significance (P) for the difference in performance due to head rotations. "ns" indicates not significant.

P-values	*monitor*	*binoc HMD*	*monoc HMD*	*Vision Sport*
size 4	ns (0.99)	ns (0.22)	ns (0.49)	ns (0.3)
size 3	ns (0.72)	.072	0.026	-
size 2	ns (0.32)	ns (0.18)	0.013	ns (0.15)
size 1	ns (0.69)	0.00009	0.0002	-

4. ACCOMMODATIVE FACILITY (FLIPPER BARS)

4.1 Design

Some display systems subjectively feel more straining than others. We have sought for a method to quantitatively test the level of visual strain, directly *after* the use of a display system. Previous studies have tried fixation disparity[3] and a range of other tests[7], but with only limited success. We have chosen to measure the level of accommodative facility, the ability of the eye to alter its accommodative and convergent status. Since it requires activity of both the intra-ocular and the extra-ocular muscles[8], any kind of visual strain is expected to have an effect on the measurement.

Accommodative facility tests the number of times the subject can switch fixation between a near and a far target in one minute. "Flipper bars" were used, consisting of a pair of plus 2 diopter and minus 2 diopter lenses in a holder which can be flipped from one side to the other[8]. The subject views a text chart at 40 cm distance through either the plus or minus 2D lenses. As soon as the chart can be read, the experimentor flips the lenses from plus to minus or vice versa and waits till the subject again reports that the chart is clear. The test can be performed binocularly or with either eye separately. Typical values are 14 cycles (or flips) per minute when tested monocularly and slightly less when tested binocularly. The binocular task is slightly harder since it requires a change in both accommodation and convergence; the monocular task only requires a change in accommodation. Data were recorded during 3 minutes only, so as to minimize the chance that the test would interfere with strain due to the display system.

4.2 Methods and Results

4.2.1 Effect of practice

Accommodative facility was tested starting three minutes after the 24 minute reading task described in Chapter 2. Accommodative facility was also tested during the section of the day that the subject rested. These latter measurements provide a baseline level of eye strain. During one minute the two eyes were tested together, followed by the right eye and the left eye. During the rest period the accommodative facility gradually improved with repetition, indicative of the typical practice effect[8]. The scores recorded during the test period showed no improvement of the scores over time, indicating that the reading task limits the accommodative facility.

4.2.2 Effect of display system

The flipperbar scores averaged over the eight subjects are shown in Figure 2. The scores in the heading "rest" are the averages during the section of the day that the subject rested, providing the baseline level of eye strain. Large differences between display systems occur, indicating that accommodative facility indeed is a sensitive method to measure visual strain. The accommodative facility in rest and after viewing the monitor do not differ. The scores after viewing the Vision Sport HMD are reduced to nearly half their value, showing significant strain. The Virtual io HMD scores intermediate, the monocular version being more straining than the binocular version. All subjects showed more eye strain with the monocular systems.

4.2.3 Effect of monocular versus binocular testing

It can be seen in Figure 2 that the accommodative facility of the right eye (viewing the display) is more reduced after viewing the monocular HMD's than the left eye (not viewing the display). The flipper score on the monocular systems fell to 63% and 73% of the score for the binocular systems for the right eye and the left eye respectively. Therefore, even though the left eye is not viewing the image in the monocular displays and in principle could rest, it suffers nearly equally as much as the right eye. The strong coupling between the two eyes causes both eyes to strain even though only the right eye is useful in the monocular reading task. The binocular scores follow the same trend.

5. DISCUSSION

5.1 Comparison of task performance and accommodative facility

Task performance and accommodative facility correlate remarkably well as can be seen by comparing Figures 1 and 2. Even within subjects and between subjects the correlations are fair. With other words, a display system that is harder to read also tends to be more straining. The high consistentcy among the 8 subjects (not shown here) indicates that the sample size of 8 subjects was sufficiently large to extend the conclusions to be general. Note that, except for the Vision Sport HMD, the difference in reading difficulty is not due to display quality. The effort to read leaves its mark as a visual strain for at least 10 minutes after the 24 minute reading task. The level of visual fatigue, how long the effect persists, has not been tested in the present experiment.

5.2 Potential causes of eye strain

Three potential causes for eye strain have been identified, but the relative importance of each has yet to be examined. However, it is very likely, as discussed below, that each plays a significant role in eye strain induced by viewing a head mounted image.

5.2.1 Stationary versus moving observers: the Vestibular-Ocular and Opto-kinetic Responses

The results indicate that head rotations while viewing a monitor does not affect the task while head rotations with a HMD significantly reduces the reading ability. This result can be ascribed to the "vestibular-ocular reflex" (VOR) and the "opto-kinetic reflex" which cause the eyes to counterrotate to compensate for head and body rotations[9,1,10]. The VOR originates in the vestibular system and is independent of visual input. The opto-kinetic reflex is caused by optic flow seen by the visual system. The counter-rotating reflex allows for steady fixation of objects while moving in or through the world. Thanks to this reflex the monitor remains equally legible while moving the head back and forth. However, for the HMD's this very important reflex looses its functionality since the image moves along with the head. In order to read the text, the counter-rotating reflex needs to be suppressed. Peli[11] showed that the VOR response is hard to suppress when the motion is active and during accelerations. In our study the subjects were not able to entirely do so either.

Of the three HMD's the immersive HMD suffers the least from head rotation. Since the natural (visually rotating) world is not visible, only the VOR reflex is active. With the see-around HMD's, eye-rotation is also induced by the opto-kinetic reflex. The strength of the eye--rotation reflex is therefore expected to be related to the amount of the direct surroundings that are visible.

Fixation needs to be most precise to read the smaller letters; for this reason the effect of head motion is greatest on the smallest text. The need to suppress an innate reflex is probably one of the three main causes of eye strain with HMD's.

5.2.2 *Binocular rivalry*

Binocular rivalry occurs when the two eyes receive different inputs and causes eye fatigue[12]. The two monocular displays cause significant rivalry while the binocular displays do not. The effect of rivalry on eye strain is modulated by the relative brightness of the informative and the non-informative image. In the experiment the informative image (here the display) was of higher brightness than the relatively dim surroundings[13] (Table I). Most of the time the display suppressed the surround image and only occasionally the reverse. The eye strain due to binocular rivalry (in case of the two monocular HMD's) would probably have been higher still in brighter surroundings.

5.2.1 *Fixed accommodation and convergence*

A characteric and unnatural aspect of HMD images is that the accommodation is fixed. The general consensus has been that prolonged *near* work leads to eye strain[14,15,16]. The accommodation distance of the four display systems was 63 cm for the monitor, 4 m for the Virtual IO HMD, and adjustable for the Vision Sport HMD. The flipper test alternates between 22 cm (4.5 D) and 2 m (0.5 D) viewing distance. It is very unlikely that the resulting eye strain is simply a function of the accommodation setting of the displays. However, not changing accommodation for 24 minutes may cause a reduction in accommodation facility.

5.3 Implications for HMD design

The methodologies worked out in this study make it possible to objectively measure the level of visual strain of a display. The four systems which were tested differ significantly in both visual performance and strain. Here the results are generalized to form a few rules of thumb.

- Visual strain after just 24 minutes of viewing is real and can be quantified.
- Reading small print or viewing high resolution images with a see-around HMD while moving through the world is a bad idea. A larger FOV with the same number of pixels may therefore be preferable.

- Most likely monocular displays are more straining than binocular displays, and see-around HMD's are more straining than immersive HMD's.

This study does not address any long term effects of viewing HMD's.

6. CONCLUSIONS

Visual performance and visual strain can be objectively measured. The results show that eye strain is very significant in some HMD designs and less so in others. Even slight head motions severely reduce the visibility of detailed information in HMD's, particularly in see-around HMD designs.

7. ACKNOWLEDGEMENT

The research presented in this paper was financed by the Royal Dutch Army, and performed as part of a thesis requirement of the School of Optometry at Utrecht[17].

8. REFERENCES

1. Peli E. (1995). "Real vision & virtual reality". Optics & Photonics News 6, 28-34.

2. Regan E.C. (1995). "Some evidence of adaptation to immersion in virtual reality". Displays 16, 135-139.

3. Wann J. P., Rushton S. & Mon-Williams M. (1995). "Natural problems for stereoscopic depth perception in virtual environments". Vision research, 35, 2731-2736.

4. Barbur J.L., Forsyth P.M. & Wooding D.S. (1989). "Eye movements and search performance". Optometry & Vision Science, 253-264.

5. Blake R., Zimba L. & Williams D. (1985). "Visual motion, binocular correspondence and binocular rivalry". Biological Cybernetics, 52, 391-397.

6. Wagenaar W.A. (1969). "Note on the construction of digram-balanced latin squares". Psychological Bulletin 72, 384-386.

7. Padmos P. (1988). "Visual fatigue with work on visual display units: the current state of knowledge". In Eds. G.C. vanderVeer and G. Mulder *Human computer interaction: psychonomic aspects*, 41-52. Berlin, Springer Verlag.

8. Daum K.M. (1991). "Accommodative Facility". In Eds. Eskridge, J.B. & Amos, J.F. & Bartlett, J.D. *Clinical procedures in optometry*, 687-696. J.B. Lippincott, Philadelphia.

9. Carpenter R.H.S. (1988). *Movements of the eyes*. Pion Limited, London.

10. Wells M.J. & Griffin M.J. (1984). "Benefits of helmet-mounted display image stabilisation under whole-body vibration". Aviation, Space, and Environmental Medicine, jan, 13-18.

11. Peli E. (1990). "Visual issues in the use of a head mounted monocular display". Optical Engineering 29, 883-892.

12. Kooi F.L. (1993). "Binocular configurations of a night-flight head-mounted display". Displays 14, 11-20.

13. The image to surround luminance ratio is at most 1:1 for the monocular Virtual io HMD and 20:1 for the Vision Sport due to the shaded visor.

14. Miller R.J., Pigion R.G., Wesner M.F. & Patterson J.G. (1983). "Accommodation fatigue and dark focus: the effects of accommodation free visual work as assessed by two psychophysical methods". Perception & Psychophysics 34, 532-540.

15. Kintz R.T. & Bowker D.O. (1982). "Accommodation response during a prolonged visual search task". Applied Ergonomics 13, 55-59.

16. Birnbaum H. M. (1985). "Symposium on nearpoint visual stress". American Journal of Optometry & Physiological Optics, 361-381.

17. Bergen J.F. (1996). Optometrische evaluatie en gebruikscomfort van Helmet mounted displays. Scriptie Hogeschool van Utrecht, Faculteit Optometrie.

PROCEEDINGS
EUROPTO
SERIES

Imaging Sciences and Display Technologies

Jan Bares
Christopher T. Bartlett
Paul A. Delabastita
José L. Encarnação
Nelson V. Tabiryan
Panos Trahanias
Arthur R. Weeks
Chairs/Editors

7–10 October 1996
Berlin, FRG

Sponsored by
Technologiestiftung Innovationszentrum Berlin eV
IS&T—The Society for Imaging Science and Technology
EOS—The European Optical Society
SPIE—The International Society for Optical Engineering
The Commission of the European Communities, Directorate General for Science, Research, and Development

Published by
SPIE—The International Society for Optical Engineering

Volume 2949