PERGAMON

Vision Research 38 (1998) 2053–2066

Vision Research

The visual effects of head-mounted display (HMD) are not distinguishable from those of desk-top computer display

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Received 12 June 1997; received in revised form 15 October 1997

Abstract

Concerns about potentially harmful effects on the visual system due to the use of head mounted displays (HMDs) in general, and stereoscopic systems in particular, have been raised in the literature. Most of the concerns were based on studies measuring visual function changes following short-term use of HMDs. This study measured functional changes in binocular vision, accommodation, and resolution following 30 min use of HMD in both stereoscopic- and non-stereoscopic modes, and compared them to changes following the same task performed on a desk-top CRT display. No functional differences were found between HMD and CRT and most measured changes were too small to be considered clinically meaningful. An evaluation of subjective comfort found a statistically significant difference in the impression of comfort between the CRT and the HMD in stereoscopic mode, with the latter being less comfortable. It can be concluded that the functional changes reported following short term use of HMDs are not specific to stereoscopic presentation and do not differ from those caused by desk-top CRT display.

Keywords: Binocular; Asthenopia; Stereo vision; Simulator sickness; Instrument myopia

1. Introduction

Head-mounted displays (HMD) are being developed and marketed in growing numbers for a variety of applications. Though most commonly associated with entertainment applications (e.g. virtual-reality rides and computer games) other applications (e.g. remote control and operations, maintenance, engineering, and scientific simulations) are also being developed. The differences between the real world for which the human visual system is adapted and the optics of HMDs could result in discomfort and possibly permanent visual changes [1–4]. Worries about possible harmful effects accompany the introduction of almost any new and widely-used technology. Such concerns were raised with the introduction of television, computers, microwave-ovens, and most recently, cellular-phones.

There is little doubt that using a HMD can cause some changes in the visual system. Changes in accommodative and binocular status have been recorded following reading [5,6], using a computer display [7] and using head mounted night vision devices [8]. Changes are expected because adaptation to the environment is a major characteristic of biological systems. Therefore changes per se are not of concern. Only changes that may have a negative effect on function or comfort, or those that may have an impact over an extended period of use, are of interest. If such negative effects are found, they should be critically evaluated for their magnitude and their impact on the users. As noted by Wilson [9], the fact that riding in a car can cause motion sickness for some people is not considered reason enough to ban the use of cars for transportation.

This study was designed to evaluate the effects of using a HMD on the visual function and comfort of the user. Concerns regarding the ill effects of HMD use fall into four categories: (1) simulator sickness resulting from vestibular-visual conflicts, (2) accommodative difficulty presumed to be associated with instrument myopia, (3) binocular function difficulties due to a mismatch between the device and the individual user's visual system [e.g. different inter-pupillary distances (IPDs)] and (4) binocular (and possibly accommoda-

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0042-6989/98/$19.00
PII: S0042-6989(97)00397-0

tive) difficulties associated with the de-coupling of the natural relationship between accommodation and convergence in stereo binocular HMDs employing image disparity. Each of these will be discussed in turn.

(1) Simulator sickness associated with general feelings of discomfort, often associated with nausea or other stomach symptoms, was reported following the use of flight simulators [10]. The possibility of similar symptoms following HMD use has been raised as a major concern in the adoption of these devices (an entire issue of Presence 1992;1(3) was dedicated to articles on simulator sickness). Simulator sickness is thought to result from a conflict between the vestibular signal about head motion and the visual signal from the head-bound image. Under normal viewing conditions, without compensating eye movements images shift on the retina with head movement. However, when viewed with a HMD, images do not shift with head motion [11,10,2,12]. This problem is expected to occur with both monocular and binocular HMDs. To determine the extent of simulator sickness with each type of display, a subjective questionnaire was administered after each device use.

(2) Improper accommodation (related to instrument myopia) occurs with the use of various optical devices, including HMDs [13]. Instrument myopia has two possible consequences for HMD use. First, accommodative spasm, which causes a temporary myopic shift, has been suspected as a precursor to the development of permanent myopia [14]. It was suggested (with no direct evidence) that long-term HMD use, especially by children, may cause or accelerate the development of myopia. For this and other reasons, many manufacturers warn against the use of their devices by children. For example, Sony recommends restricting the use of their bi-ocular, non-stereo, Glasstron™ system to persons 15 years of age or older. To examine the possibility that accommodative spasm in the HMD leads to transient myopia, we measured changes in refraction immediately following HMD and CRT use.

The second effect of instrument myopia relates to resolution and image clarity. The visual acuity of the user may be optimal at the resting focus [15,16]. Improper accommodation in the device may manifest itself as perception of blur or difficulty focusing by the user. The perception of blur and difficulty focusing were explored in a questionnaire. Blur alone has also been hypothesized to be a possible cause of the development of myopia [14].

(3) Mismatches between the HMD and the user's visual system can result in blurred or double vision. This can result from differences between convergence demand and the accommodative demand [17] due to improper optical design of the display, blurred or double vision may occur when the user first looks through such a system. For smaller mismatches, vision may remain clear but continued use may cause eyestrain. With continued use the visual system begins to adapt to the new demand using prism adaptation [18], which causes a change in heterophoria. If adaptation is incomplete, continued use may result in further eyestrain, which may be aggravated by stereo. If adaptation is fairly complete, then once the observer stops using the device, re-adaptation to the real world is needed. HMD users with marginally functioning visual systems may suffer from more symptoms [1,19]. Blurred and double vision can also result from differences between the user's IPD and the system's inter-optical distance (IOD) possibly leading to phoria and fixation disparity changes [20]. This concern was based on the known effects of lens decentration in spectacles, although as discussed below, the situation with HMD is somewhat different. There are no reports of double vision persisting after the use of HMD. However, reports of blur, eye strain and headaches after short periods of use are abundant [1,21]. Phoria, fixation disparity, and fusional ranges were measured to see if changes of concern occur following HMD use.

(4) There are numerous suggestions in the literature that stereo disparity in binocular HMDs produces additional difficulties for the user [2,3,22]. The conflicting demands on the convergence and accommodation systems associated with such displays may cause more changes to visual function than the use of bi-ocular systems in which the same image is presented to both eyes [22]. Mon-Williams et al. [1] found more changes in phoria, acuity, and fixation disparity using a stereo HMD than had been found in a different study using a bi-ocular HMD [22]. The effect of de-coupling the convergence and accommodation demands was not established in these studies because different subjects participated in each and the two HMDs tested differed in important ways not related to the stereo versus bi-ocular difference. The current study makes a three-way comparison among a HMD used in stereo mode (STEREO), the same HMD used in the bi-ocular mode (MONO), where the same image is presented to both eyes, and a desk-top display (CRT). This design allows us to compare the effects of stereo HMD versus bi-ocular HMD in the same subjects using the same display and the same task. The comparison of the MONO and CRT conditions allows us to determine the changes in visual function that are specific to the HMD environment.

In addition to the parameters already discussed, the study included measurements of visual acuity and contrast sensitivity, as well as tear break-up (TBU) time, which is a measure of tear layer integrity and can corroborate complaints (assessed with a questionnaire) of dry and irritated eyes associated with display use. Those complaints are presumed to be a result of reduced rate of blinking during display use.

The basic approach was to compare the effects of playing a computer game using the HMD for 30 min to the effects of playing the same game on a desk-top CRT monitor (control condition). This control condition is considered risk free by most people. Millions of computer games are sold world wide and no serious visual problems have been reported, although various visual and non-visual health concerns about the use of CRTs have been discussed [23,24]. It is an appropriate control because the eyes are used in a similar way and the activity is otherwise identical in terms of concentration demands and interest.

The general study design was based on the guidelines proposed by the ISO [25] for the testing of new display devices for word processing work-stations. The specific testing procedures selected were guided by the recent literature on visual function with HMDs. For example, because Mon-Williams et al. [1] found statistically significant changes in many visual parameters with 10 min of HMD use, we chose 30 min of device use for our study. More recent studies [11,22] also reported visual changes and symptoms with 30 min or fewer of use.

2. Methods

2.1. Apparatus

The i-glasses™, manufactured by Virtual I/O (Seattle, WA) was used for testing. This system has been used by other researchers studying visual effects of HMDs [11,26] and was compared with other HMD systems in some of those studies. The i-glasses system is a binocular HMD that can be operated either in STEREO mode, with two disparate images presented on the two displays, or in MONO mode, where the same image is presented to both eyes. The images are presented on color Seiko Epson LCD displays (789×230 pixels) and viewed through an optical system composed of mirrors and lenses; the field of view is $25 \times 20°$. The display rests on the forehead, and there is ample clearance for the user's spectacle frame to fit under the display.

The i-glasses HMD is not designed to be adjusted to the individual user. The system's IOD is fixed at 61 mm and the wide exit pupils permit use by persons whose IPDs differ from this value by as much as 10 mm. System focus is fixed at a distance of 4 m (0.25 diopters, D), at the center of the screen, and convergence demand of the optical system is fixed at a distance of 2.4 m (0.42 D or 2.5 Δ for the user with 61 mm IPD) (Fig. 1). This design should permit comfortable, clear binocular viewing of the whole screen, without stereo, as defined by Percival's criterion using Morgan's population norms [27] (see Fig. 1). It induces a low level of base-out prism effect at the center of the screen that is balanced by a small base-in effect at the edges of the screen (compensating for the effect of field curvature of ~ 0.7 D).

The computer game used was Ascent (Gravity, San Francisco, CA), selected from the Games CD distributed by Virtual I/O. This game can be played on a standard CRT as well as the i-glasses, and two game versions are available: a STEREO (binocular) version that provides disparity between the two eyes' images to represent depth and a MONO (bi-ocular) version that provides both eyes with the same image without disparity. Subjects were instructed in game use and rules during introduction to the first device. The game activity consisted mainly of jumping from one rock to another, progressing up a virtual canyon while avoiding obstacles and falling. It should be noted that playing the game did not require much head movement, nor were there extreme motion representations within the game. The levels of motion (both real and virtual) with this game were similar to those present in previous studies [1,11].

In STEREO the next stone to be stepped on is provided without disparity. In the i-glasses this corresponds to convergence at 2.4 m (2.5 Δ) and focus at 4 m (at the center of the screen). The far cliffs in the game are provided with uncrossed disparity corresponding to a convergence distance of 4.8 m (1.3 Δ for an observer with 61 mm IPD; see Fig. 1). The far stones are at a slightly closer distance of 3.8 m (1.6 Δ). The current stone, seen mostly in the lower peripheral field, is at 1.9 m (4.7 Δ). As can be seen in Fig. 1, these values keep the nominal observer within the comfort zone for the center of the screen while placing some divergence pressure at the edges of the screen (far cliffs). These moderate values of disparity were designed into the game by its developers without any relation to the i-glasses design. The close match between the two at the center of the screen represents compliance with general design criteria for both hardware and software [12].

Acuity, contrast sensitivity and fixation disparity were measured using the B-VAT II SG (Mentor O&O, Norwell, MA), a multipurpose computerized vision testing device [28]. Visual acuity can be tested with randomly selected letters presented at each level. This feature is especially important in a study like this one where the subjects are presented with the same tests multiple times, because it eliminates the possibility of memorization. The SG version of the B-VAT tests contrast sensitivity using a three-alternative forced-choice, joystick response to an oriented sinusoidal grating [29], enabling very fast testing. The binocular version includes liquid crystal shutter glasses for dichoptic presentation and provides testing of fixation disparity and the associated phoria. The availability of a fixation disparity test at distance is of particular importance because changes in fixation disparity are

considered to be clinically relevant [17] and have been reported by Mon-Williams et al. [1] following use of HMDs. The computer control of the B-VAT also permits fast testing and quick transition from test to test.

2.2. Subjects

Test subjects were free of eye disease and binocular abnormalities. Candidates were excluded if, for any one of the parameters, they fell outside the range of 'normal' which accounts for $\approx 95\%$ of the general population. The magnitude of the exclusion criteria for each parameter are shown in Table 1. The complete eye exam included: a health assessment of the external eye, the anterior segment, and the retina, and a few functional screening tests in addition to the tests used in the study. These included color vision screening, evaluation of eye movement control, monocular acuity, pupilometry, and subjective refraction. Functional assessment was completed before health assessment tests which required dilating the pupils. Description of the various test procedures are provided in the Appendix.

Thirty-seven subjects (21 men) ranging in age from 18 to 49 years completed the study. An additional 18 subjects were excluded at the initial eye exam on the basis of various exclusion criteria. The large number is a result of excluding subjects who fall outside of the 95% range for any one of the many parameters tested. Reasons for exclusion included: exophoria ($n = 6$), esophoria ($n = 3$), vertical phoria ($n = 4$), fixation disparity ($n = 1$), tropia ($n = 1$), and reduced contrast sensitivity at 2 c/deg ($n = 3$). Two more subjects did not show up for follow-up and were therefore excluded from the analyses. Subjects used their customary optical correction in their customary format (glasses or contact lenses). For the four subjects who used reading glasses (or who remove their distance glasses for reading), the near point habitual correction was used during near point testing.

Subjects were recruited through a newspaper advertisement. They read and signed an informed consent, were paid for participation in daily increments, and were free to leave the study at any stage. Subjects excluded from the study due to pathology found in the screening were informed of the reason and referred to optometric or ophthalmologic follow-up, as needed.

2.3. Design

Each subject used each device (HMD STEREO, HMD MONO and CRT); the order of presentation was counter-balanced across subjects to randomize the possible effects of familiarity with the game, the devices, and the testing procedures. Subjects were randomly assigned to one of the six possible presentation orders (Table 2). Testing of each device occurred on separate days, with 2–7 days between tests.

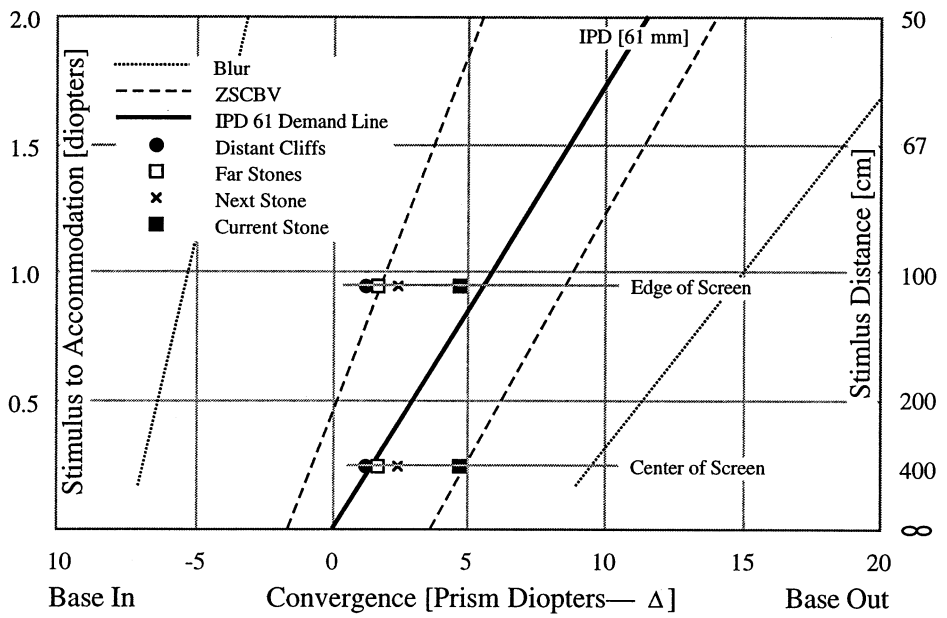

Fig. 1. Accommodation and convergence stimuli diagram illustrating the demands placed on an observer with 61 mm IPD using the i-glasses in the STEREO mode of the Ascent game. The thick solid line represents the demand line of real world physical stimuli. The dashed line on both sides include the comfort zone (by Percival's criterion). The comfort zone was derived from the zone of single clear binocular vision (ZSCBV) based on Morgan's norms of vergence to blur (dotted lines). The i-glasses optical design is illustrated by the position of the 'x'-'Next Stone' (which is presented with no disparity in the game). The difference between the center of the screen and the edge of the screen accounts for ~ 0.7 D of field curvature. For no disparity features both the center and edge of the screen are included in the comfort zone. For the other game features, presented with disparity, only the far features at the edges of the screen are outside the zone. These areas are rarely of interest in the game and are therefore unlikely to be fixated.

Table 1
Normal values, values used for excluding candidates from study, and values determined to be clinically meaningful changes for the various parameters tested

	Normal values	Exclusion criteria	Meaningful changes
Refraction	NA	NA	±0.50 D[a]
Visual acuity	20/20	<20/40	One line
Fixation disparity			
Horizontal		>2 min	2 min
Vertical		>1 min	1 min
Stereo	<40 s[b]	>60 s	20 s
Phoria at 6 m			
Horizontal	1 Δ exo[c]	>3 Δ eso	4 Δ
		>5 Δ exo	4 Δ
Vertical	0	>1 Δ	1 Δ
Phoria at 40 cm			
Horizontal	3 Δ exo[c]	>7 Δ eso	4 Δ
		>13 Δ exo	4 Δ
Vertical	0	>1 Δ	1 Δ
Vergence at 6 m			
BI	x/7/4[c]	x/< 1/<0	x/4/4
BO	9/19/10[c]	<1/< 3/<2	6/6/4
Vertical	3/1.5[b]	<1/<0	2/2
Vergence at 40 cm			
BI	13/21/13[c]	<5/<13/<3	6/6/6
BO	17/21/11[c]	<7/<9/<0	6/6/6
Vertical	3/1.5[b]	<1/<0	2/2
FCC	0–2.5 D by age	NA	0.75 D
NRA	+2.00 D[c]	NA	−0.75 D
PRA	−2.37 D[c]	NA	+0.75 D
TBU	28 s[d]	NA	15 s
Contrast sensitivity			
2 c/d	85[e]	<50	0.3 log units
3 c/d	140[e]	<75	0.3 log units
6 c/d	140[e]	<75	0.3 log units

In addition to these parameters, subjects were excluded from study if any of the following were found during the initial screening: strabismus, nystagmus, reporting diplopia in any position, restricted eye movements, noncomitant movement or pain in any position, any pupillary abnormality, irregular or sluggish pupillary response, cataract, any other media opacity, retinal lesions, optic nerve abnormality, or IOP over 22 mmHg in either eye.
FCC, fussed cross cylinder; NRA, negative relative accommodation; PRA, positive relative accommodation; TBU, tear break-up time; BI, base in; BO, base out; many of these terms are explained further in the Appendix.
[a] Ref. [38], [b] [37], [c] Morgan cited in [17], [d] [39] and [e] [29].

At each test session, and during the baseline measurements, the following visual parameters were measured in the order listed here:

1. accommodative status by refraction (auto refractor)
2. binocular (OU) visual acuity at distance (6 m, 20 ft) with habitual correction
3. fixation disparity (lateral and vertical) at distance
4. stereoacuity at near (40 cm, 16 in.)
5. phoria (lateral and vertical) at distance and near (cover-test with prism-bar and Von-Graefe in the phoropter)
6. vergence (horizontal and vertical) at distance and near
7. accommodative reserve by fuse cross cylinder (FCC)
8. convergence reserve measured by negative and positive relative accommodation (NRA and PRA, respectively)
9. TBU time
10. contrast sensitivity at distance (OU) at three spatial frequencies (2, 3, and 6 c/deg)

This order was selected to enable rapid testing of those parameters thought likely to return to baseline quickly.

Each measurement was taken three times: before, immediately following and 30 min after device use. Baseline data obtained during the screening provided an estimate of the random error used for statistical power calculations. Post-use testing determined if changes after device use were larger than random error measurements and to compare the effect with that of the control condition. The follow-up (post-post) measurements were used to determine if significant task-induced physiological changes return toward baseline within a limited time frame. In the study of Mon-Williams et al. [1], some of the changes found were reported to return to baseline after 5 min.

2.4. Procedure

Before introduction to each device, subjects completed the battery of tests described above. This process took 20–30 min the first time; subsequent repetitions were faster as the subjects became familiar with the procedures.

Following pre-use testing, subjects were introduced to the device to be used on that day and were introduced or reminded of the game's controls and rules. For HMD sessions, they were instructed on fitting the display to the head and positioning it in front of the eyes to assure a comfortable and stable position. The i-glasses and CRT were used with habitual refractive correction. Subjects sat in a comfortable chair under normal office illumination and played for 30 min.

Immediately following, the same battery of vision tests was administered in the same order. This was followed by the discomfort questionnaire. Thirty min of free activity time followed, after which they returned for the final battery of tests. The procedure was the same for each of the three devices.

2.5. Data analysis

Analyses were aimed at testing whether HMD use (in either MONO or STEREO mode) is associated with changes in visual parameters that are different from changes associated with CRT use. A 3×3 (test time:

pre, post, post-post) (devices: MONO, STEREO, CRT) within-subjects ANOVA was calculated for each parameter. Interactions, if found, indicate that changes in the measured parameters over time (pre, post, post-post) differed among the devices tested. The hypothesis that HMD use does not result in adverse changes in the parameter of question was analyzed using t-tests.

The data were further analyzed to determine if any changes found in visual function were clinically meaningful. Values for clinically meaningful changes were determined for all parameters prior to testing on the basis of existing data and the author's and Dr Ted Kadet's clinical judgment. Typically, two standard deviations of the population mean was considered to be a meaningful change (Table 1). Clinically meaningful changes are necessary to calculate the power of the statistical tests [30], which is important whenever no statistically significant changes are found and are also important to the discussion of data where difference are found.

If no statistically significant interactions were found in the 3×3 ANOVA, further statistical testing was not necessary. Nevertheless, whenever a main effect of device or of time-of-test was found, the data were further analyzed in an effort to understand its sources.

2.6. Assessment of discomfort

Subjects were given a discomfort questionnaire modified from the questionnaire found in the International Standard [25]. The modification permitted three-way comparisons among the three test conditions. Data were analyzed as recommended in the Standard with the proper modification for a three-way analysis, in which each condition was compared against the two other conditions.

After testing with the first device, subjects were asked to assess its effects with respect to a list of characteristics of visual discomfort and mark their responses on the scales provided on the form (Fig. 2). The language used to present the form to the subject was modified minimally from the language recommended [25].

Subject's responses were scored at the completion of the study (see Table 2 for the possible outcomes of the questionnaire and the corresponding scoring). The individual scores for each of the six scales were added together, resulting in scores ranging from -6 to $+6$. Positive scores indicate that the test device was judged to be more comfortable than the control device and negative scores indicate that the test device was judged to be less comfortable than the control device. A score of zero indicates that the test device and the control device were judged to be equally comfortable. Individual ratings were examined using a t-test.

2.7. Power calculations

The study tested the hypothesis that using the HMD is not associated with any adverse changes to the visual system that differ from changes associated with using desk top CRT. It also tested the hypothesis that changes associated with the use of a STEREO HMD do not differ from changes associated with the use of a MONO- or bi-ocular HMD. Both statistical and clinical meaningful differences were assessed. The statistical power required for each parameter tested was calculated to verify that there were sufficient number of subjects tested to reject those hypotheses if they were in fact false.

The procedure for calculating power involves setting the α and β errors, and determining the size of the change, Z, on each parameter which would be consid-

Table 2
The six presentation orders used to counter-balance effects of training and familiarity. The possible outcomes of the discomfort questionnaire. The last three columns give the scoring associated with each possible outcome

Presentation orders	Possible outcomes	STEREO vs. CRT	MONO vs. CRT	STEREO vs. MONO
STEREO MONO CRT	CRT = STEREO = MONO	0	0	0
MONO CRT STEREO	CRT = STEREO < MONO	0	1	−1
CRT STEREO MONO	CRT = STEREO > MONO	0	−1	1
STEREO CRT MONO	CRT < STEREO = MONO	1	1	0
MONO STEREO CRT	CRT < STEREO < MONO	1	1	−1
CRT MONO STEREO	CRT > STEREO = MONO	−1	−1	0
	CRT > STEREO > MONO	−1	−1	1
	CRT = MONO < STEREO	1	0	1
	CRT = MONO > STEREO	−1	0	−1
	CRT < MONO < STEREO	1	1	1
	CRT > MONO > STEREO	−1	−1	−1
	STEREO < CRT < MONO	−1	1	−1
	MONO < CRT < STEREO	1	−1	1
Sum		0	0	0

> Represents 'better than' in the response.

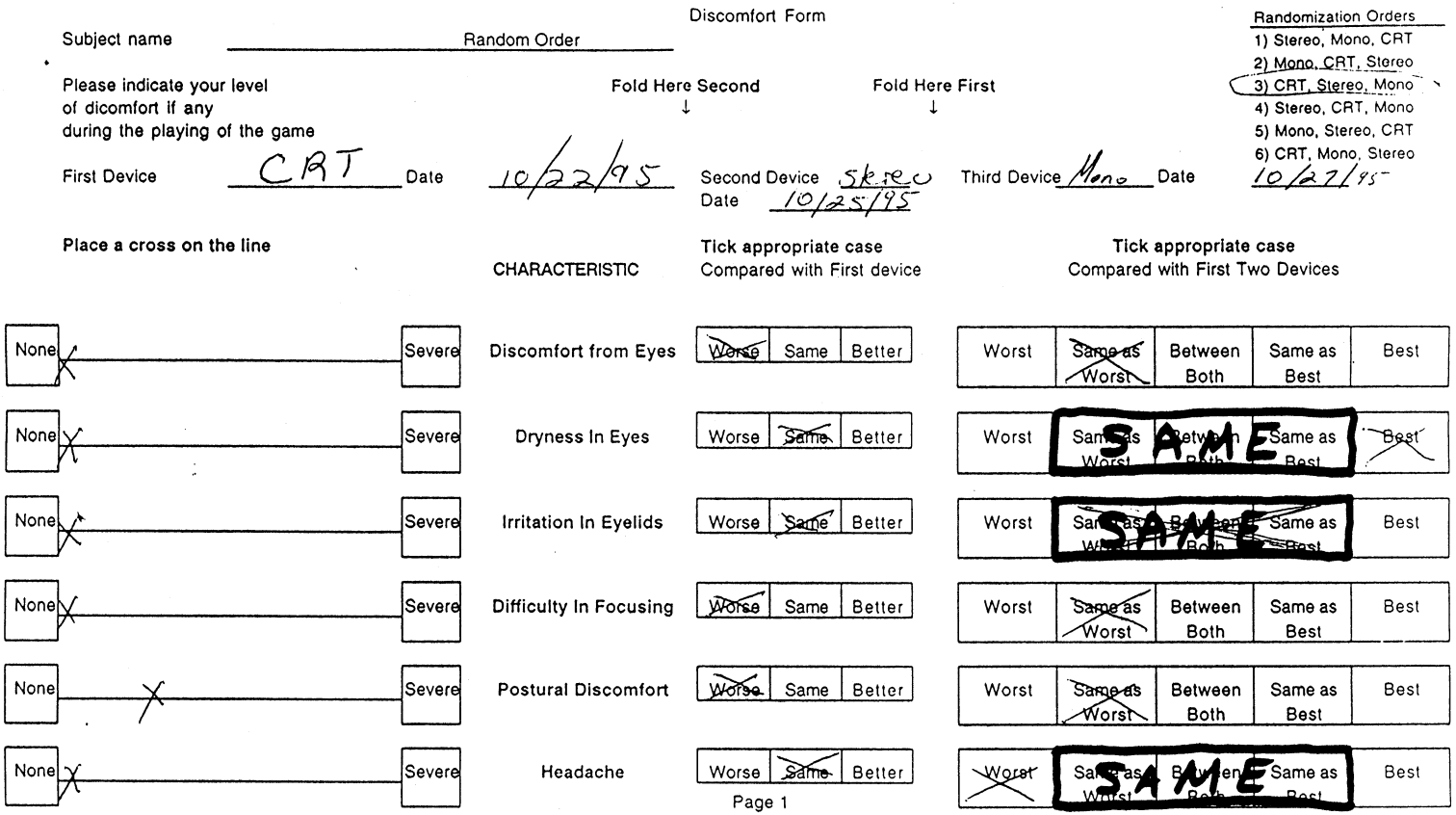

Fig. 2. Example of the form used for the evaluation of subjective discomfort. The form was folded as indicated and was unfolded as the study progressed. Following first device use, the subject indicated on the form, using a continuous scale, the level of discomfort for each of the six items. Following second device use, the subject was presented with his or her previous responses as marked and selected the response comparing the second device to the first one using the three alternatives provided. Following third device use, the form was completely unfolded and the subject compared the last device to the previous two on a five level scale. The scale was modified following testing of the second device to three levels when indicated, as shown by the dark squares marked 'same.'

Table 3
Means and standard deviation (SD) of all subjects for all of the parameters taken at the various testing points (note the generally small effects of all devices for all parameters)

	Spherical equivalence OD[a] (D)	Acuity OU (×/20)	Fixation disparity lateral (arc min[b])	F.D. vertical (arc min[c])	Near stereo (arc s)	Cover test distance lateral (Δ[b])	Cover test distance vertical (Δ)	Cover test near lateral (Δ[b])	Cover test near vertical (Δ[c])	Distance phoria lateral (Δ[b])	Distance phoria vertical (Δ[c])	Distance vergence Bi[d] BR (Δ)	Distance vergence BI[d] RE (Δ)	Distance vergence BO[d] BL (Δ)	Distance vergence BO[d] BR (Δ)	Distance vergence BO[d] RE (Δ)	Distance OD BU[e] BR (Δ)	Distance OD BU[e] RE (Δ)	Distance OS BU[e] BR (Δ)	Distance OS BU[e] RE (Δ)
Baseline	−1.11	18	0	0	32	0	0	4	0	1	0	11	5	11	15	6	3	1	2	0
	(2.31)	(3.2)	(0.4)	(0.3)	(10)	(0.5)	(0)	(3)	(0)	(1)	(0.2)	(4)	(2)	(4)	(6)	(2)	(1)	(1)	(1)	(1)
MONO	−1.11	18	0	0	29	0	0	4	0	1	0	8	4	11	14	7	3	1	2	0
Pre	(2.30)	(3.8)	(0.5)	(0.6)	(11)	(0.3)	(0)	(3)	(0)	(2)	(0.2)	(2)	(2)	(4)	(5)	(4)	(1)	(1)	(1)	(0)
MONO	−1.10	18	0	0	29	0	0	4	0	1	0	9	4	14	13	8	3	1	3	0
Post	(2.34)	(3.4)	(0.5)	(0.3)	(11)	(0.0)	(0)	(3)	(0)	(2)	(0.7)	(3)	(1)	(5)	(6)	(5)	(1)	(1)	(1)	(1)
MONO	−1.11	19	0	0	28	0	0	4	0	1	0	8	4	12	14	8	3	1	3	0
Post-post	(2.28)	(6.1)	(0.7)	(0.4)	(11)	(0.0)	(0)	(3)	(0)	(2)	(0.3)	(2)	(1)	(6)	(7)	(5)	(1)	(1)	(1)	(1)
STEREO	−1.07	17	0	0	28	0	0	3	0	1	0	9	4	11	13	8	3	1	3	0
Pre	(2.24)	(3.4)	(0.2)	(0.5)	(10)	(0.2)	(0)	(3)	(0)	(2)	(0.0)	(3)	(2)	(4)	(6)	(4)	(1)	(1)	(1)	(1)
STEREO	−1.06	17	0	0	27	0	0	4	0	2	0	9	4	11	12	7	3	1	3	0
Post	(2.32)	(3.5)	(0.2)	(0.4)	(10)	(0.0)	(0)	(4)	(0)	(2)	(0.6)	(3)	(2)	(5)	(5)	(4)	(1)	(1)	(1)	(1)
STEREO	−1.14	18	0	0	27	0	0	4	0	1	0	8	4	11	13	7	3	1	3	0
Post-post	(2.30)	(3.5)	(0.2)	(0.4)	(13)	(0.0)	(0)	(3)	(0)	(2)	(0.4)	(2)	(2)	(5)	(5)	(4)	(1)	(1)	(1)	(1)
CRT	−1.15	17	0	0	27	0	0	4	0	1	0	9	3	11	12	7	3	1	2	0
Pre	(2.34)	(3.0)	(0.7)	(0.3)	(11)	(1.0)	(0)	(3)	(0)	(2)	(0.2)	(3)	(2)	(4)	(5)	(4)	(1)	(1)	(1)	(1)
CRT	−1.22	18	0	0	28	0	0	4	0	1	0	8	3	12	14	7	3	1	3	0
Post	(2.32)	(4.6)	(0.3)	(0.4)	(14)	(0.6)	(0)	(3)	(0)	(2)	(0.4)	(2)	(2)	(4)	(6)	(4)	(1)	(1)	(1)	(0)
CRT	−1.12	17	0	0	28	0	0	4	0	1	0	8	3	11	12	7	3	1	3	0
Post-post	(2.31)	(3.2)	(0.4)	(0.3)	(11)	(0.0)	(0)	(2)	(0)	(2)	(0.4)	(2)	(2)	(5)	(6)	(4)	(1)	(1)	(1)	(1)

	Near phoria lateral (Δ[b])	Near phoria vertical (Δ[c])	Near vergence BI[d] BL (Δ)	Near vergence BI[d] BR (Δ)	Near vergence BI[d] RE (Δ)	Near vergence BO[d] BL (Δ)	Near vergence BO[d] BR (Δ)	Near vergence BO[d] RE (Δ)	Near OD BU[e] BR (Δ)	Near OD BU[e] RE (Δ)	Near OS BU[e] BR (Δ)	Near OS BU[e] RE (Δ)	FCC (D)	NRA (D)	PRA (D)	Tear break-up OD (s)	Contrast sensitivity at 2 c/deg	Contrast sensitivity at 3 c/deg	Contrast sensitivity at 6 c/deg
Baseline	6	0	17	26	12	13	21	7	4	2	4	1	0.64	2.65	−2.05	7	117	188	212
	(4)	(0.2)	(6)	(6)	(4)	(5)	(7)	(4)	(1)	(1)	(1)	(1)	(0.63)	(0.54)	(1.18)	(4)	(69)	(106)	(101)
MONO	6	0	16	23	13	17	18	5	4	2	4	1	0.70	2.73	−2.45	5	92	158	183
Pre	(5)	(0.4)	(4)	(6)	(4)	(5)	(7)	(5)	(1)	(1)	(1)	(1)	(0.58)	(0.58)	(1.29)	(2)	(46)	(64)	(101)
MONO	6	0	18	22	11	19	17	5	4	2	4	1	0.59	2.54	−2.55	5	93	165	165
Post	(4)	(0.7)	(6)	(7)	(4)	(9)	(7)	(7)	(1)	(1)	(1)	(1)	(0.52)	(0.55)	(1.31)	(2)	(43)	(69)	(81)
MONO	6	0	17	24	12	21	17	5	4	2	4	1	0.63	2.63	−2.43	6	98	152	166
Post-post	(5)	(0.4)	(4)	(6)	(4)	(9)	(7)	(6)	(1)	(1)	(1)	(1)	(0.52)	(0.51)	(1.45)	(4)	(39)	(63)	(100)
STEREO	5	0	18	23	12	17	19	6	4	2	4	1	0.66	2.67	−2.34	6	93	151	188
Pre	(5)	(0.2)	(6)	(6)	(4)	(6)	(6)	(6)	(1)	(1)	(1)	(1)	(0.59)	(0.48)	(1.15)	(3)	(41)	(57)	(94)
STEREO	6	0	18	23	12	16	17	5	4	2	4	1	0.64	2.74	−2.53	6	89	159	186
Post	(5)	(0.5)	(6)	(7)	(5)	(9)	(7)	(6)	(1)	(1)	(1)	(1)	(0.58)	(0.52)	(1.27)	(4)	(44)	(64)	(96)
STEREO	6	0	19	23	12	15	18	6	4	2	4	1	0.72	2.78	−2.45	5	86	150	161
Post-post	(5)	(0.5)	(6)	(7)	(5)	(2)	(6)	(6)	(1)	(1)	(1)	(1)	(0.56)	(0.80)	(1.36)	(3)	(36)	(69)	(81)
CRT	7	0	20	23	12	22	18	7	4	2	4	1	0.68	2.63	−2.28	6	108	168	164
Pre	(4)	(0.0)	(5)	(6)	(5)	(8)	(7)	(6)	(1)	(1)	(1)	(1)	(0.58)	(0.51)	(1.31)	(3)	(41)	(65)	(85)
CRT	6	0	19	22	12	15	17	5	4	2	4	1	0.65	2.61	−2.43	6	95	163	167
Post	(4)	(0.5)	(6)	(7)	(5)	(5)	(7)	(6)	(1)	(1)	(1)	(1)	(0.58)	(0.50)	(1.31)	(3)	(38)	(90)	(90)
CRT	6	0	19	23	12	18	17	6	4	2	4	1	0.76	2.73	−2.36	6	98	155	176
Post-post	(5)	(0.6)	(5)	(7)	(4)	(7)	(7)	(6)	(1)	(1)	(1)	(1)	(0.62)	(0.51)	(1.38)	(3)	(40)	(55)	(97)

[a] Average of OD and OS measurements used in analysis. [b] Negative, eso; positive, exo. [c] Negative, L hyper; positive, R hyper. [d] Sum of BI and BO ranges used in analysis. [e] Sum of OD BU and OS BU ranges used in analysis.

Table 4
Mean results and standard deviations (S.D.) for responses to the discomfort questionnaire

	STEREO vs. CRT	MONO vs. CRT	STEREO vs. MONO
Discomfort from eyes	−0.19 (0.66)	0.05 (0.57)	−0.16 (0.55)
Dryness in eyes	−0.16 (0.55)	−0.11 (0.46)	−0.11 (0.39)
Irritation in eyelids	−0.22 (0.48)	−0.16 (0.44)	−0.05 (0.40)
Difficulty in focusing	−0.46 (0.65)	−0.19 (0.62)	−0.24 (0.72)
Postural discomfort	−0.24 (0.64)	−0.16 (0.65)	−0.03 (0.64)
Headache	0.03 (0.50)	0.00 (0.41)	0.05 (0.40)
Discomfort sum	−1.24 (2.14)	−0.57 (2.19)	−0.54 (1.99)

For each item the response can range from −1.0 to +1.0 and the summed response from −6.0 to +6.0.

ered clinically meaningful, where Z is expressed in S.D. units. For all the parameters, where S.D. data were available, the meaningful change values (Table 1) resulted in $Z \geq 1.00$.

Following the formulation recommended by ref. [25], the number of subjects required for a comparison between two devices (for $\alpha = \beta = 0.05$, and $Z \geq 1.0$) was estimated to be ~ 23. The three-way comparison used in the current study required 50% more subjects for a total of ~ 34. Thirty-seven subjects completed the study. Following data collection, power was recalculated on the basis of the variability of the current data. These calculations confirmed that the statistical power available was sufficient to reject the hypothesis that there was no difference between the devices tested for all parameters if those differences existed (only two of the parameters—contrast sensitivity of 2 c/deg and PRA—resulted in Z values of 0.9; the remainder were ≥ 1.0).

3. Results

The data from the various tests of visual function for all the testing conditions averaged across subjects are shown in Table 3. Average changes following device use are small in all cases and never approach the level of meaningful change listed in Table 1. None of the parameters showed a statistically significant interaction between the device used and time-of-test in the ANOVA. We can conclude that the i-glasses HMD in either MONO or STEREO mode resulted in no changes in any of the parameters tested that were statistically different from those induced by the CRT. Very few statistically significant main effects of time-of-test were found, and the changes in each of these variables were too small to be clinically meaningful. A main effect of time-of-test indicates that whatever changes occur while playing the game are independent of the device used.

The only significant difference found for the subjective impression of comfort was between the CRT and the STEREO conditions. On a scale of −6 to +6, the difference was −1.2 units, indicating that the STEREO device was less comfortable. Examination of the data (Table 4) from the six scales showed that the largest difference was for 'difficulty in focusing' followed by 'postural discomfort'.

Both the hypothesis that HMD use in either STEREO or MONO modes for 30 min causes no visual changes that are different from those caused by desk top CRT use for the same task and the hypothesis that STEREO mode causes no visual changes that are different from those caused by the MONO bi-ocular mode of operation can not be rejected. Nevertheless, due to the limited experience gained so far with these devices, it was interesting to examine the data further to see if any specific conclusions can be drawn regarding specific tests or effects on individual subjects. These analyses are reported below.

3.1. Refractive error

For each subject the average change for both eyes was analyzed. Only one subject had as much as 0.5 D change towards myopia following use of the CRT. Similarly, one subject had a 0.75 D change towards myopia between the baseline testing and the pre-testing of the first device. Such changes in refractive error are within the reproducibility of measurements with the auto refractor. Even if these are accurate measurements, the data indicates that this small change in refractive error is possible with any near work and is not specific to the stereoscopic or binocular nature of the HMD.

There were small errors (< 0.5 D) in correction for most subjects between their refractive error and their habitual correction (mean difference = 0.05 D OD and 0.00 D OS). Only one subject had > 1 D error in one eye, the other eye was −0.75, and the subject had no glasses or contact lenses.

3.2. Visual acuity at distance

The mean difference in each comparison was < 0.05 (1 ft). One subject had a change in acuity > 0.25 following i-glasses use (STEREO mode) but returned to baseline level at post-post testing. One subject had a similar change following CRT use and also returned to baseline level following rest.

3.3. Fixation disparity

Changes in fixation disparity were very small (< 0.2 min of arc on average), and they appeared to be the result of random variations in measurement. A large number of subjects had measurable fixation disparity before testing and meaningful changes in lateral disparity following device use (six subjects had a lateral change of 2 or more min of arc: two with MONO, four with CRT). Nine subjects had a change of 1 arc min or more of vertical disparity (two with MONO, five with STEREO, two with CRT). This represents either a larger variability of fixation in this population or lack of accuracy in performing the fine alignment task needed for this test. Many of the recorded changes resulted from one non zero measurement. Similar changes in fixation disparity were found between the baseline data and the pre-first device lateral fixation disparity data. Since both measurements were taken before any device use (on different days), any differences represent the level of variability in measurement, the population, or both.

There was a small (0.08 min of arc) change in fixation disparity (in the exo direction) following STEREO use that was significant by one-tailed t-test. That small difference disappeared in the post-post measurement. In fact the fixation disparity following 30 min of rest was more eso than before device use, but that difference was not statistically significant.

3.4. Stereoscopic acuity at near

The data showed a very small trend towards improvement in stereo acuity following the use of the STEREO device. Average changes for all of the devices were < 2 s of arc. Only five subjects had a reduction of acuity of ≥ 20 s following device use (two with MONO, one with STEREO, and two with CRT). Following the short rest period, three of the five returned to the pre-test level.

3.5. Phoria at distance

The alternate-cover test showed essentially no phoria in this population (only two subjects had small lateral phoria). The phoropter measurements revealed small levels of lateral phorias in almost all the subjects, but both the mean and the S.D. were smaller than those reported in the general population (Morgan's norms cited in [27]).

No statistically significant effects or interactions were noted under the cover test for lateral or vertical phoria, nor was there any effect noted for vertical phoria in the phoropter. There was no significant interaction for the lateral phoropter measurement either; however, there was a significant main effect of device, and the interaction between device and time-of-test approached significance ($P = 0.054$) for the lateral measurements in the phoropter.

For lateral phoria, the mean change after i-glasses MONO use was 0.1 Δ (prism diopters) towards exophoria, which was not statistically significant. Following STEREO use, the change was 0.9 Δ towards exophoria, which was found significant by t-test. This result is similar to that found by Howarth and Costello [31] for the same display. Following a rest period of 30 min, there was another statistically significant change (0.7 Δ) in the other direction, and no statistical difference was found between the pre-device test and post-post test. Following CRT use there was a shift of 0.3 Δ towards esophoria. This different direction of change between the STEREO and CRT conditions probably accounts for the interaction term approaching significance.

In each test device, about one-third of the subjects changed towards esophoria, while the rest changed toward exophoria or did not change. It should be noted that change towards exophoria is generally of less clinical concern. Five subjects had a change of 4 Δ or more following STEREO use (four out of the five were in the exo direction). This finding replicates data in the literature indicating that some individuals show large changes of phoria with HMD use [1,11]. It is not known if such changes could cause harm, or if they simply represent the natural adaptation to the visual demands imposed by the display [2]. Change in the exo direction is in line with the design of the device, as described in Section 2. The fact that a larger change was associated with the STEREO condition may indicate that the nature of the disparity in the game played is also contributing to the change.

3.6. Effect of user's IPD

The mismatch between the user's IPD and the system's IOD has been suggested as a potential source of a prismatic effect, which may lead, through prism adaptation, to changes in phoria [20,22,32], and can cause discomfort symptoms with fixed IOD systems [33]. For a system with a large focal distance, such as the i-glasses (4 m), the prismatic effect should be minor [2]. Thus the user's IPD should not be correlated with the changes in phoria found following device use. The correlation between the phoria change between pre-

and post-test and the user's IPD (measured with a pupilometer) were relatively small (-0.03, 0.25, and 0.23 for the MONO, STEREO, and CRT conditions, respectively) and none were statistically significant. Note that the correlation for the CRT condition, which should show no effect of IPD, is of the same magnitude as that for the STEREO condition.

3.7. Phoria at near

There was no vertical phoria evident by cover test measurement for any subject in any condition and only five subjects had any vertical phoria measured in the phoropter. The correlation between the cover test data and the phoropter data for lateral phoria at baseline was 0.53 and was statistically significant.

The device × time-of-test interaction approached significance for the near phoropter measurements. As in the distance measurement, phoria changed towards exophoria with use of the STEREO (average change 0.9 Δ) and towards esophoria with use of the CRT (average change 0.7 Δ). These changes were significant. The MONO condition resulted in very little average change (0.03 Δ). For the CRT condition the difference between pre-device and post-post testing remained small and in the eso direction, and was not statistically significant. For the STEREO condition the difference of ~ 1 Δ towards exophoria remained even following rest. This small change in phoria posture towards exophoria found in both the near and distance measurements following the STEREO device probably represents prism adaptation. A few subjects had changes of ≥ 4 Δ in each condition and two subjects had changes of 10 Δ. These data indicate that large changes in phoria occur in some subjects following use of any of these devices and are not specific to HMD, or to STEREO display in particular.

3.8. Vergence

To analyze changes in vergence, for each measurement (break point and recovery point) the base-out and base-in results were added together. The sum of these measurements represents the zone of single binocular vision (ZSBV) for the break and recovery tests, respectively. The ANOVAs for both distance and near lateral and vertical vergence ranges found no significant interactions in either the break or the recovery data.

There was a significant main effect of device for the lateral break and recovery measurements at distance. In both cases the ranges were smallest for the CRT.

There was also a significant main effect of time-of-test for the near lateral vergence break and recovery ranges, indicating a small reduction in range with all three test devices. The mean change was ≤ 2 Δ in all conditions. The changes between the baseline measurement and pre-device measurement were much larger (5–6 Δ for the break), indicating that some of the reduction is simply a result of the subjects' growing familiarity with the test.

3.9. Accommodation

A reduction in the focusing ability of the eyes is indicated when either the NRA or the PRA is decreased in absolute value. The subjects demonstrated about a 0.75 Δ need for bifocal based on their FCC results and low PRA at baseline. Such under-correction is expected in a population of this age. The minimal changes seen following any device use was never > 0.2 Δ.

3.10. Tear break-up time

TBU times measured (average 6–7 s) were lower than those reported in the literature (10 s in ref. [34]).

3.11. Contrast sensitivity

Contrast sensitivity was measured at 2, 3, and 6 c/deg. The ANOVA found no significant interaction in any of the comparisons. The data at 2 c/deg was most variable, probably because it was always the first spatial frequency tested. The ANOVA revealed a significant main effect of device, indicating that the 2 c/deg results were worse for the STEREO condition than for the other two. The same reduction in sensitivity relative to the other devices was measured before and after the STEREO use, indicating only that on average subjects performed worse on the day they were tested with the STEREO device. There was no difference between the pre-and post-test measures.

4. Discussion

The data reported here show no harmful nor statistically significant changes to the visual system associated with use of the i-glasses HMD in either STEREO or MONO mode relative to the use of a desk-top CRT display. For most measured variables, no change was found with use of any of the devices. The presumed stressful effects of using a stereo display as compared with a bi-ocular display [3,22] were also not found. This study is the first to directly test this hypothesis by comparing the same device, software, and subjects using the two modes of display. It clearly demonstrates that when the range of disparity used to present depth is moderate and stays within the comfort zone, the effects of stereo display does not differ from bi-ocular display. It is possible that a stereo display that presents much larger disparities and a task requiring repeated oscillations between large distances may induce larger effects.

The subjective ratings confirm previous findings that discomfort and eye strain of a vague nature are associated with the use of HMDs and are greater than those associated with the use of a CRT. Some of this discomfort could be related to postural discomfort (see Table 4), but low grade visual symptoms are present as well. The causes of this ocular discomfort have not been identified, but the use of any new optical instrument may elicit such complaints. For many people, a small change in the refractive correction with spectacles results in a similar or larger level of discomfort [35] even when vision is improved. This type of discomfort usually disappears with one or two weeks of wear without any known consequences.

The level of subjective symptoms found in the current study was substantially lower than those reported by others [1,11,31]. This discrepancy may be due to the survey methods used. In other studies, the comparison was aimed at determining the change in symptoms following HMD use, an approach adopted from the investigation of simulator sickness in pilots. This method of questioning regarding lists of symptoms before the study session may tend to prime the subjects by directing their attention to various feelings of discomfort during the test and thus bias their responses. The method employed here, adopted from the comparison of workstation displays, compared discomfort across the devices tested. One-third of our subjects used the CRT first and the HMDs were used first by the remaining subjects. In all cases there were very low levels of discomfort for the first device regardless of its nature, and there were no subjects that withdrew from the study or interrupted the session due to illness. This is in stark contrast to other studies that reported widespread, serious discomfort [1,11]. Although some of the differences between studies may be attributable to the differences in devices used and the tasks performed, Howarth and Costello [11] found much more discomfort using the same device and a similar task, as well as with a less active task (a chess game) [11], it is believed from this study that most of the complaints reported resulted from substantial priming of the subjects to expect at least some of the symptoms contained in the pre-test symptom check-list.

The conclusions drawn here from the vision testing differ substantially from those derived by previous investigators [1,11] despite the fact that for various parameters the changes found here were similar to those found in the previous studies. In particular, the changes in phoria found here are similar to those reported by Mon-Williams et al. [1], who used a different HMD, and to those reported by Howarth and Costello [11], who used the same device. The changes found here with HMD were compared to changes that occurred with a control device, and no difference was found.

The level of change is of consequence as well. In seeking to define clinically meaningful changes, recorded changes were evaluated not only for their statistical significance, but also for their clinical significance. If one assumes that some changes in the visual system will occur with the use of any display device, and that these changes are related in some way to the design of the display or the method of its use, then sufficiently careful testing will reveal these changes. However, such changes are of concern only if they are of sufficient magnitude or if their effects are cumulative. There is no indication that changes in visual function following HMD use are cumulative and most studies (including the one reported here) have found that values return to baseline levels a short time after display use was interrupted [1,36]. Future studies should evaluate the possibility of cumulative effects over extended periods of use.

Acknowledgements

This study was supported by Virtual I/O Inc. I wish to thank Bob McRuer for his constant and enthusiastic support of this effort, Laura Haak for excellent help in monitoring the study and controlling the paperwork, as well as instructing the subjects to the device and game use. Elisabeth Fine consulted on statistical and design issues, and Angela Labianca contributed data input and helped in data analysis. Most of all I wish to thank Dr Kadet and all the staff at the Hope Clinic in Seattle, WA for hosting the study at their facility and carrying out all the difficult tasks needed to collect the data. Erik Viirre and Elisabeth Fine reviewed an earlier draft of the manuscript. The author was supported by NIH grants EY 05957 and EY 10285 during preparation of the manuscript.

Appendix A. Detailed protocols for vision tests

Unless stated otherwise, subjects wore their habitual correction. Some of the tests were administered by certified ophthalmic technicians using automated equipment; others were administered by a practicing optometrist. Personnel were trained to perform each of the procedures, record data, and manage patient flow before data collection began. Tests marked with an asterisk were administered by a technician. All other tests were administered by the optometrist, who also performed the additional functional and health assessment tests listed in Section 2.3.

A.1. Visual acuity*

Acuity was tested binocularly (OU) using the B-VAT system set to display one randomly selected letter at a time. Testing began at a letter size corresponding to 6/12 (20/40). Five letters of the same size were presented sequentially. If the subject was able to correctly identify four of the five letters, the size was decreased until this standard was no longer attained. The size was then increased one step. If the subject was again able to name four of the five letters at that size, it was recorded as the acuity.

A.2. Fixation disparity (distance; horizontal and vertical)*

Using the B-VAT, the Associated Phoria Test was used to screen for fixation disparity. The magnitude of fixation disparity, in min of arc, was measured using the standard procedure recommended in the B-VAT manual only for subjects that showed fixation disparity on screening. This procedure includes at least one reversal staircase returning with a smaller step size (1 min of arc) for the final alignment. Either horizontal or vertical disparities were measured as indicated by the screening test.

A.3. Stereo acuity (near)*

The Randot stereo test was modified to permit repeated testing while preventing subjects from memorizing the answers. The ten stereo acuity targets (each containing three circles) were cut from three test sets. The targets from each test were remounted on a card in a pseudo-random order. The back of each card was marked with the acuity (disparity) level corresponding to the stimuli order.

For each test, one card was randomly selected from the three available. Polarized glasses were worn over spectacle or contact lens correction. Subjects indicated which of the three circles appeared to float in front of the others (right, middle, or left) in all ten sets. When uncertain the subject was required to guess. The smallest disparity correctly reported by the subject was recorded.

A.4. Cover test

The cover-uncover test to detect phoria or tropia and the alternate-cover test for phoria magnitude estimates were administered as described in ref. [37].

A.5. Phorometry

The Von-Graefe method for phoria measurements, lateral and vertical vergence ranges at distance and near, and the accommodation testing using the Fused Cross Cylinder (FCC) test and the Negative Relative Accommodation/Positive Relative Accommodation (NRA/PRA) were carried out in the phoropter applying standard clinical procedures [37].

A.6. Tear break-up time

TBU time was measured at the slit-lamp using fluorescein dye and following standard clinical procedures [37].

A.7. Contrast sensitivity*

Contrast sensitivity was tested binocularly using the Jack (three alternative forced choice) system of the B-VAT. Three spatial frequencies were tested (2, 3, and 6 c/deg) and always in that order. A staircase of three reversals was used with the default two-down, one-up procedure.

A.8. Refraction

Refractive error in each eye was measured using the Canon RK-2 auto refractor. For subjects wearing contact lenses, measurements were taken with the lenses to avoid the need to manipulate the eyes and to be able to perform the refraction as soon as possible following device use. For spectacle-wearing subjects auto refractor measurements were taken with no correction.

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