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Luminance of the Surround and Visual Fatigue of VDT Operators

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Luminance distribution in the visual field is considered as one of causal factors with a significant influence on visual fatigue, especially for intensive and extended Video Display Terminal (VDT) work. The aim of the study was to define visual fatigue of VDT operators for different values of surrounding luminance. Experiments were carried out in laboratory conditions under 3 lighting conditions. Only 1 lighting parameter—the luminance of the wall behind the display (surrounding luminance)—changed. Visual fatigue was measured both by a subjective evaluation of different visual complaints (asthenopic symptoms) and by objective measurements of changes in the following visual functions: accommodation, convergence, habitual horizontal phoria, critical fusional frequency (CFF), and visual acuity. The same experiments were done for CRT (Cathode Ray Tube) and LCD TFT (Liquid Crystal Display with Thin Film Transistor) screens. The results of the study have shown that there was no significant influence of the value of surrounding luminance on the asthenopic symptoms for either type of screen. A general tendency towards bigger visual complaints for LCD TFT than for CRT participants was found. An objective evaluation of visual fatigue demonstrated a tendency towards bigger changes in visual functions with an increase of surrounding luminance for both screens. Statistical analysis of the results has shown that surrounding luminance influences significantly the reduction of the accommodation amplitude (significance level $< .05$).

luminance visual fatigue CRT screen LCD TFT screen

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1. INTRODUCTION

One of the main functions of lighting is to minimize the demands on the visual system by providing lighting parameters in the luminous environment appropriate to the activity (visual task difficulty). Lighting requirements are determined by the satisfaction of three basic human needs (Standard No. prEN 12464:1996; European Committee for Standardization [CEN], 1996):

- safety;
- visual performance (i.e., workers are able to perform their visual tasks even under difficult circumstances and during longer periods);
- visual comfort (i.e., workers have a feeling of well-being).

Lighting design should provide an environment in which people, through the sense of vision, can function effectively, efficiently, and comfortably (Rea, 1993). The way of establishing appropriate lighting parameters, especially for new and complex types of visual work, is through modeling different lighting conditions and investigating both the subjective evaluation of lighting and the objective measurements of visual performance or visual fatigue. Visual performance is usually evaluated by measuring the time needed to perform the task and the number of mistakes. Visual fatigue manifests itself in the weakening of a variety of visual functions. It usually manifests itself in the form of specific complaints reported by persons who perform strenuous and extended visual tasks. The term that is used to describe symptoms associated with the use of eyes is asthenopia. The symptoms of asthenopia are (North, 1993)

- ocular: sore, tired, tender, itchy, heavy, dry, burning, or aching eyes;
- visual: blurred or double vision, focusing problems;
- systemic: headache and general fatigue.

The sources of visual fatigue are probably the weakening of the oculomotor system, perception, neuronal transmission, and processing of visual stimuli. The most important elements of the oculomotor system are accommodation, modification of the optical power of the eye, external oculomotor muscles system responsible for coordinated eye movements (including vergence movements), and muscles responsible for the pupilary reflex. The introduction of Visual Display Terminals

(VDTs) was associated with an increase of visual problems amongst VDT operators and interest in this subject (Matula, 1981). Some studies have estimated that up to 40% of VDT users suffer daily from asthenopic symptoms (Bergqvist, 1984). A variety of environmental factors are suspected to contribute to the rise of asthenopic symptoms. Some of the described aspects were microbiological (Assini et al., 1997). Also mentioned as possible causes were dry environment containing noxious particles (Messite & Baker, 1984) and viewing distance (D'Orso, Zambelli, Pierini, Assini, & Piccoli, 1997). An earlier study (Shahnavaz, 1984) revealed a low significant relationship between lighting conditions and incidence of accommodation changes among VDT operators. This could be due to the large variation in the outside light conditions during day-time measurements. There seems to be a conviction that non-uniform light distribution, which requires continuous retinal adjustments as well as frequent pupillary reactions could be a cause of asthenopic disturbances (Piccoli, 1993). It is possible that ocular symptoms of asthenopia (irritation, pain, redness, etc.) may be more linked to workroom lighting, whereas for visual symptoms (blurring, flickering, double vision, etc.) display characteristics may be more important (Bergqvist, 1984). However, there are no reports about experimental laboratory studies concerning the influence of lighting parameters on asthenopic symptoms and visual fatigue during VDT work.

There are many publications and recommendations for the design of a VDT workstation and its environment. Unfortunately, most recommendations concerning lighting parameters on computer workstations present different requirements, especially in the area of luminance distribution (balance) in the field of view (Table 1). Luminance distribution, usually defined by the luminance ratios, affects visual comfort and controls the adaptation level of the eyes, which affects task visibility and discomfort glare. Well-balanced adaptation luminance is needed to increase visual acuity, contrast sensitivity and efficiency of the ocular functions (accommodation, convergence, eye movements, etc.; prEN 12464:1996; CEN, 1996). If the luminance ratios are too high, they could cause

- fatigue,
- discomfort glare (and in specific circumstances disability glare; prEN 12464:1996; CEN, 1996).

TABLE 1. Examples of Luminance Distribution (Balance) Requirements

Source	Luminance Ratio
Standard No. PN-E-02033:1984 (Polski Komitet Normalizacyjny [PKN], 1984)	**1:3** immediate surrounding-visual task **1:10** remote surrounding-visual task **No detailed requirements for VDT workstations**
Rea (1993)	**1:3** adjacent surrounds-visual task **1:10** remote surrounds-visual task
Kokoschka and Haubner (1985)	Up to **1:20** source document-screen
Pitts (1993)	**1:3 to 1:4** room background-screen mean
Publication CIE No. 55:1983 (International Commission on Illumination [CIE], 1984)	Reflectance of the surfaces around the display, keyboard and document should be kept in the range of **0.2 to 0.5**
Standard No. ISO 9241-3:1992 (International Organization for Standardization [ISO], 1992)	Lower than **1:10** between task areas frequently viewed in sequence; Lower than **1:100** between task area and its surrounds
Standard No. ISO CD 9241-3 Add. 1:1993 (ISO, 1993; Flat panels)	Lower than **1:20** between task areas frequently viewed in sequence; Lower than **1:100** between task area and its surrounds
Standard No. ISO CD 13406-2:1994 (ISO, 1994; Flat panels)	The area mean luminance of task areas that are frequently viewed in sequence should be between **5% and 500% of peak luminance of the display**.

Notes. VDT—Video Display Terminal.

It can be seen that some recommendations listed in Table 1 differ significantly: These non-unified lighting requirements seem to be a substantial problem for proper lighting designing and the assessment of lighting conditions on VDT workstations. The interpretation of some specific results of luminance distribution, like luminance ratio between the screen and its surrounds of 1:15, could be quite different, depending on the source.

Measurements of lighting parameters carried out on VDT data entry operator stands in two Polish institutions indicated that the luminance ratio between the screen and its surrounds (the surface behind the display) was much bigger than 1:10 at 47% of the workstations and it was often bigger than 1:100 (Konarska et al., 1992; Wolska, Bugajska,

& Konarska, 1994). This was caused by excessive values of the luminance of the surface behind the display (daylight influence) and by negative polarity of the screens (which were used in normal work conditions). Negative polarity is still normally used at data entry workstations and the cashiers' and clerks' stands in banks and post offices in Poland (this is connected with software design). Very high luminance ratios of about 1:300 for far field were also noted by Laubli, Hunting, and Grandjean (1981).

Different lighting conditions at the studied workstations could not account for the influence of such big luminance ratios on visual fatigue and for choosing one of the recommendations in Table 1. It seemed to be interesting to study the influence—if there was any—of luminance ratios on visual fatigue.

The objectives of the study were

- to define how different values of surrounding luminance (i.e., the wall behind the display), which produced luminance ratios between the screen and its surrounds in the range of 1:10 to 1:100 and bigger than 1:100, influence visual fatigue;
- to define the level of visual fatigue with different luminace ratios using a subjective evaluation of visual complaints (asthenopic symptoms) and optometric measurements (changes in visual functions);
- to compare visual fatigue for CRT (Cathode Ray Tube) and LCD TFT (Liquid Crystal Display with Thin Film Transistor) displays.

2. PARTICIPANTS

Participants were selected according to the criteria of age (under 30 years old), gender (female), and eye state. Full ophthalmologic examinations of participants were performed. Participants were selected according to the following criteria: no known visual defects, visual acuity ranging between 1.0 and 1.5 on Snellen charts for distance, spherical refractive errors less than $\pm$ 0.5 Dsph, astigmatism less than $\pm$ 0.5 Dcyl, no abnormalities in the examination of the anterior segment or fundus of the eyes, no systemic (e.g., diabetes, arterial hypertension) or neurologic (e.g., epilepsy, migraine) diseases. Refraction was measured with an autorefractometer Topcon (Japan) RM-A 6500. Selection was careful enough to eliminate factors such as refractive errors, illness, age, and gender, which are suspected to contribute to fatigue. For example, Gunnarson and Ostberg (1977) found that workers with smaller refractive errors (especially astigmatism) are likely to be predisposed to asthenopic symptoms. Some results stated that women are more predisposed for asthenopic symptoms than men (Bergqvist, 1984).

At a result of ophthalmologic examinations, 66 healthy young adult Polish females volunteered as participants in this study. They were randomly divided into two investigation groups: CRT and LCD TFT groups. Characteristics of those groups are presented in Table 2. All participants underwent training in VDT work before the experiments. They had to become familiar with the visual task simulated by a computer program and the way to do each kind of test was explained. After that, participants carried out each of the seven specific types of tests simulated by a computer program. Participants were instructed that before experimental session they should be well rested and should not do any VDT work. In general, the participants had little experience in VDT work and most of their experience was based on classroom work and was intermittent. The date of each experiment session was set with the exclusion of premenstrual tension and menstruation of each participant. In the case of malaise, headache, or visual complaints before an experimental session, the experiment was rescheduled.

TABLE 2. Group Characteristics

Feature	LCD TFT Group	CRT Group
Number of participants	36	30
Mean age (*SD*), years	20.92 (2.22)	20.7 (1.91)
Range of age, years	18–26	18–25
First contact with VDT	for 25% of participants	for 20% of participants
Training in VDT work before experiments	all participants	all participants

Notes. LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; VDT—Video Display Terminal.

Both groups were randomly divided into three subgroups (12 participants for the LCD TFT and 10 participants for the CRT in each subgroup). Each subgroup started performing the first experiment in different lighting conditions (elimination of memorized and monotony effects on the obtained results, see Table 3). All participants had to take part in experimental sessions under three lighting conditions.

TABLE 3. Order of Experimental Sessions for Each Subgroup

Subgroup	Lighting Conditions		
1	1	2	3
2	2	3	1
3	3	1	2

3. METHODS

3.1. Lighting Conditions

An experimental study was performed under lighting modeling laboratory conditions. It was conducted under three lighting conditions achieved by general lighting (8 ceiling mounted "dark-light" fluorescent luminaires; Zumtobel [Austria], XRD 2 × 36 W) and 4 fluorescent luminaires

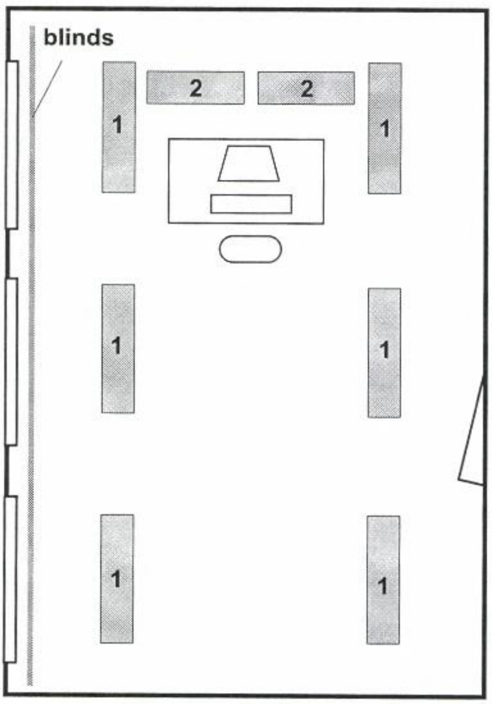


Figure 1. Lighting room diagram. *Notes.* 1—dark-light luminaires, 2—wall-washer luminaires.

(COBR Polam [Poland], OSA 2 × 36 W) for additional illumination of the wall behind the display (i.e., wall washers, see Figure 1). All luminaires were connected with a luminous flux control system, which allowed easy adjustment of lighting parameters (the flicker effect was not observed because of fluorescent tubes' high frequency electronic ballast). Windows in the laboratory room had blinds and curtains to avoid the influence of natural lighting (daylight).

TABLE 4. Lighting Parameters on a VDT Workstation (Mean Values)

Parameter	Lighting Conditions 1	2	3
Surrounding luminance, cd/m²	**45**	**205**	**602**
Screen luminance*, cd/m²			
LCD TFT screen	3.50	3.55	3.55
CRT screen	3.45	3.45	3.40
Document luminance, cd/m²	78	77	80
Table (slope) luminance, cd/m²	92	93	93
Table (horizontal) luminance, cd/m²	153	151	161
Keyboard luminance, cd/m²	59	60	60
Table (slope) illuminance, lx	345	346	346
Table (horizontal) illuminance, lx	571	566	589
Document illuminance, lx	351	355	360
Keyboard illuminance, lx	584	590	590

Notes. *—weighted mean from background and character luminances for screen filled with tests; VDT—Video Display Terminal; LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; 1, 2, 3—lighting conditions.

The aim of modeling lighting conditions was to obtain different values of surrounding luminance (i.e., the wall behind the display), which also produced luminance ratios between the screen and its surrounds above 1:10. All accepted values of surrounding luminance were taken from the range of typical values at real VDT workstations (measured on Polish data entry workstations). At the same time all lighting variants had as similar values of the other lighting parameters as possible (see Table 4). Illuminance uniformity on the working plane was bigger than 0.85 and luminance uniformity of the wall behind the screen was bigger than 0.8 for all lighting conditions. Illuminance was measured with an illuminance meter Sonopan (Poland), type L-20, equipped with a silicon photovoltaic detector (with a photopic correction filter and a cosine correction screening ring). Luminance was measured with a Minolta (Japan) luminance meter LS-110, which has a 1/3° acceptance angle and a TTL (through-the-lens) viewing system. Measurements of the character and background luminance of the screen were made with a close-up lens No. 110 (measuring diameter of 0.5–0.4 mm).

Luminance distribution in the participants' field of view was defined by luminance ratios of area mean luminances of task areas that are frequently viewed in sequence (e.g., document-screen, keyboard-screen) and between the task area and its surrounds (e.g., document-table, keyboard-table, screen-the wall behind the display). In further considerations, the luminance ratios between the screen and the wall behind the screen for both screens were taken as

- lighting conditions 1—1:13,
- lighting conditions 2—1:60,
- lighting conditions 3—1:170.

Small differences between luminance values for both screens could be neglected, according to the psychophysical Weber-Fechner Law.

The measured values of luminance ratios for the three lighting conditions just listed are presented in Table 5.

TABLE 5. Luminance Distribution

	LCD TFT Screen			CRT Screen		
Luminance Ratios	**1**	**2**	**3**	**1**	**2**	**3**
Screen-wall behind the screen	1:13	1:58	1:170	1:13	1:59	1:177
Document-table	1:1.2	1:1.2	1:1.2	1:1.2	1:1.2	1:1.2
Screen-document	1:22	1:22	1:23	1:23	1:22	1:23
Screen-keyboard	1:17	1:17	1:17	1:17	1:17	1:18
Keyboard-table	1:3	1:3	1:3	1:3	1:3	1:3

Notes. LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; 1, 2, 3—lighting conditions.

3.2. Screens' Characteristics

Parameters of the screens are presented in Table 6.

TABLE 6. Parameters of Screens

Feature	LCD TFT Screen	CRT Screen
Model	IBM 9507 Colour Display	IBM 6312-002 Colour Display
Diagonal, inches	10.5	14
Resolution, pixels	VGA, 640 × 480	VGA, 640 × 480
Polarity	negative (white on black)	negative (white on black)
Luminance, cd/m^2		
character	30.90	28.70
background	0.42	0.32

Notes. LCD TFT—Liquid Crystal Display with Thin Film Transistor, CRT—Cathode Ray Tube.

3.3. Visual Task

The visual task was simulated by a computer program and consisted of 13 different tests, which required visual work mainly with a screen with

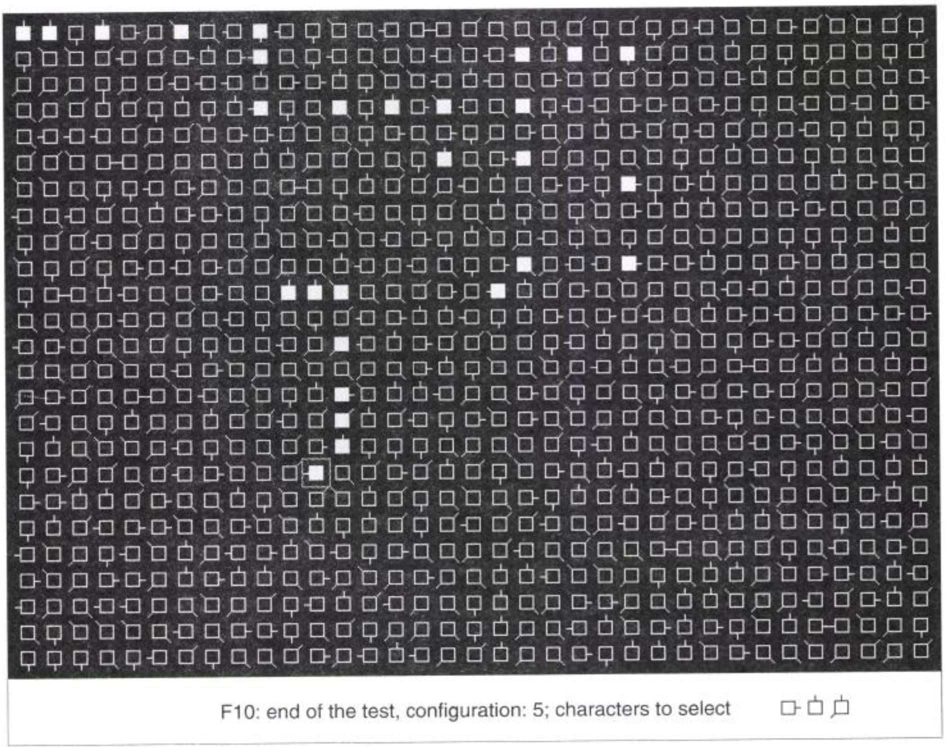
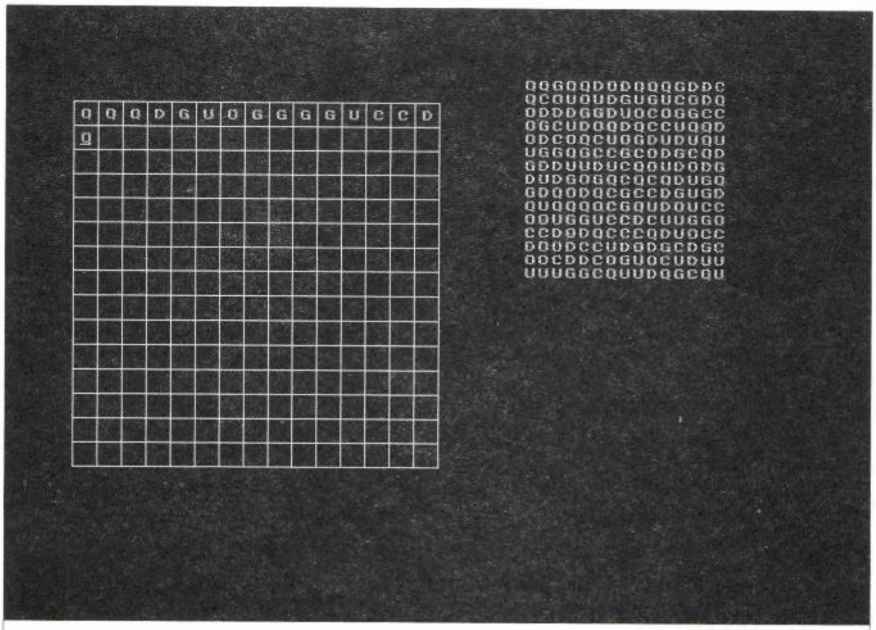
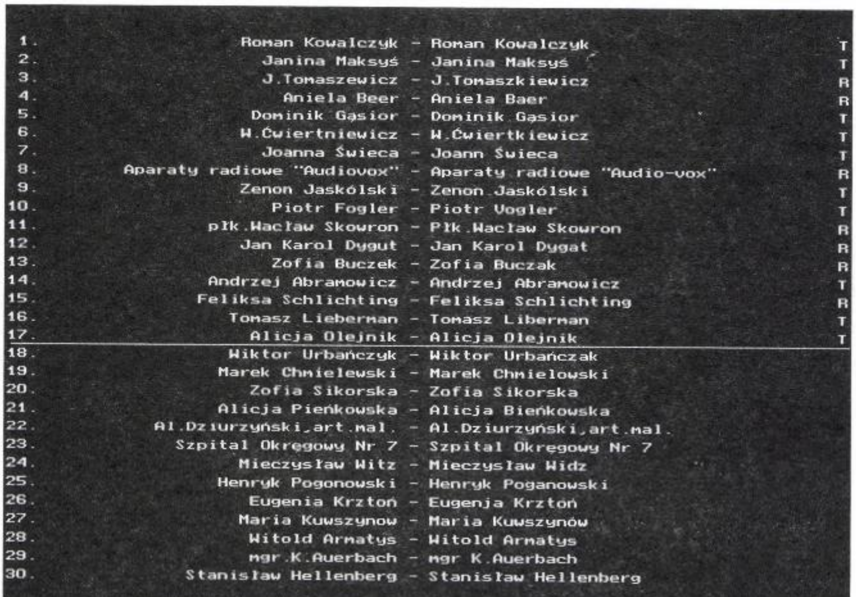


Figure 2. Presentation of Pieron's test on the screen.



Write appropriate letters (C,D,G,O,Q,U) into the chess-board squares according to the pattern on the right side on the screen. Version 1, F10: end of the test.

Figure 3. Presentation of the chess-board test on the screen.



Are the right and left sides identical? Same: "T" key, different: "R" key, F10: end of the test.

Figure 4. Name comparison test.

negative polarity. The program counted the number of mistakes and time needed to perform the task (in each test and in all the tests together). Examples of tests used in the experiments are presented in Figures 2, 3, and 4.

Participants were instructed to do the test as accurately as possible. Each participant had to take the same number of tests and the approximate time needed to perform all tests was 2 hrs (the minimum time needed to produce changes in visual functions, as had been observed in the preliminary pilot study).

3.4. Visual Fatigue Measurements

Visual fatigue was evaluated with a visual complaints questionnaire (asthenopic symptoms) and objective measurements of visual and oculomotor functions. The following measurements were performed.

- Visual acuity (VA). Monocular VA was measured subjectively with an illiterate E Snellen acuity test chart at a distance of 5 m (Bennett & Rabbetts, 1989; Kwaskowski & Mondelski, 1982).
- Near point of accommodation (NPA). It was measured by the RAF (Clement Clarke, UK) near point rule. The NPA was recorded as the first point at which the smallest line of a printed text on chart (N5, V = 0.5 on a Snellen chart for near), which was moved from a distance of 50 cm toward the participant, became illegible (London, 1991; Yeow & Taylor, 1991). To increase the accuracy of setting the NPA, the measurements were done 3 times, and then the mean value of the measurements was calculated.
- Near point of convergence (NPC, measured by the RAF near point rule). The NPC was measured by moving a single vertical line target on the RAF rule along a scale toward the eyes from a distance of 50 cm. The NPC was determined as the point at which one of the eyes of the participant started to diverge and the participant reported double vision of the target (London, 1991; Yeow & Taylor, 1991). To increase the accuracy of setting the NPC, the measurements were done 3 times, and then the mean value of measurements was calculated.
- Horizontal heterophoria (phoria) for near and for distance. It measured according to von Graefe's technique, which employs a dissociation prism over one eye and a measuring prism over the other. In this

method rotary prisms built in a Nidek (Japan) RT 600 refractor were placed in front of the participant's eyes. The prism before the right eye was turned either base-out or base-in. The prism in front of the left eye was the dissociating prism set at 6 prism diopters base-up. A single line of typed text was presented on a distant test chart (distance of 5 m) for phoria for distance and a near test chart (distance of 33 cm) for phoria for near. During the measurements the participant was instructed to keep her attention solely upon the fixed target and report when the moving target appeared, as seen peripherally, to be above the fixed one. Than the examiner could accurately read the amount of prism diopters of the prism before the right eye and stated eso- or endophorias (Bennett & Rabbetts, 1989).

- Ascending and descending threshold of critical fusional frequency (CFF, measured with the Flicker Test, Dufour [France] apparatus PV-8). Six replicate measurements of ascending threshold (increase in the frequency of light flicker from 30 Hz) and 6 replicate measurements of descending threshold (decrease in the frequency light flicker from 50 Hz) were performed. The speed of light frequency change was 1.5 Hz/s.

All the parameters were measured before and after each experimental session under the same lighting conditions. The methods (especially methods using RAF rule) are not very accurate, but they were chosen because they are easy to use, the instruments are not expensive, and they are quick. Those "simple" methods were successfully used in various studies on visual fatigue (Hedman & Briem, 1984; Horgen, 1992; Nyman, Knave, & Voss, 1985). The duration of the examination was kept from 10 to 15 min. Additionally, to increase accuracy, all measurements were repeated (the mean value of the measurements was used for statistical analysis) and the same person (an ophthalmologist) performed them. In those studies, changes of visual functions, which were statistically analysed, were a measure of visual fatigue.

The subjective evaluation of the visual complaints (asthenopic symptoms evaluation) was established by a questionnaire (Visual Analog Scale 0–100, where 0 means *no complaints* and 100 means *very intensive complaints*) filled in by the participants at the end of each experiment. The questionnaire form was taken from a standardized research protocol of the MEPS project *Muscloskeletal, visual and psychosocial stress in VDT operators in optimized environment: An international study* (Dainoff, Baliett, Blatman, Cohen, & Hecht-Dainoff, 1994; Horgen, 1992; Horgen & Aarås, 1994; Larsen, Thoresen, & Thom, 1994). The questionnaire concerned symptoms of ocular asthenopia (itching, burning, sensation of heaviness of eyelids, sore eyes, piercing, redness, and lacrimation) and visual asthenopia (sensitivity to light, blurring, and double vision). The value of the intensity and frequency of visual complaints was the measure of visual fatigue.

Additionally, a computer program, which counted the number of mistakes and the time needed to perform the visual task, evaluated visual performance.

3.5. Experimental Session Design

Each experimental session started with an interview with the participant, which consisted of filling in the questionnaire by the examiner. The questions concerned the general mood of the participant and checked the disposition of the participant before the experimental session (excluding headache, menstruation, etc.). The second step was to carry out the optometric measurements. After that the participant started to perform the visual task at the VDT workstation. The computer program

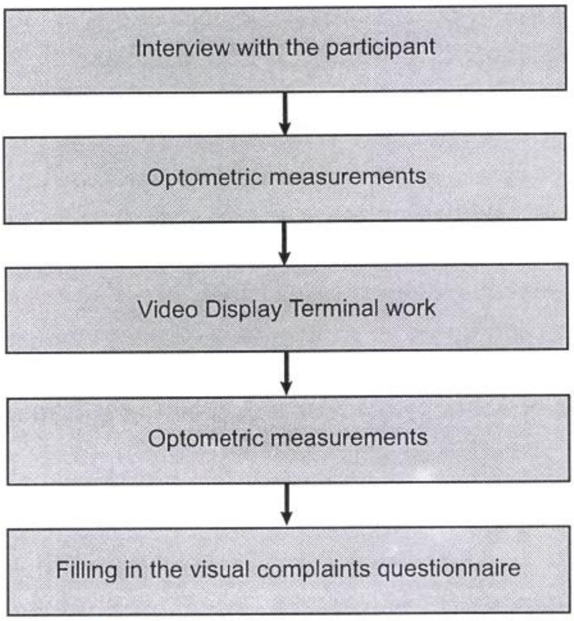


Figure 5. Experimental session design.

signaled the end of the visual task. The same optometric measurements followed immediately. The last step of the experiment was for the participant to fill in the asthenopic symptoms questionnaire (see Figure 5).

4. RESULTS

4.1. Asthenopic Symptoms Evaluation

The mean values of complaints intensity indicated that all asthenopic symptoms were assessed as small or medium regardless of lighting conditions (i.e., surrounding luminance) and the type of screen. The biggest intensities were found for redness, sensitivity to light, burning, heaviness of eyelids, blurring, and lacrimation (see Table 7). Multifactor analysis of variance (MANOVA) revealed that there was no statistically significant influence of the surrounding luminance value on asthenopic symptoms intensities for either type of screen. The same MANOVA analysis revealed that there was a statistically significantly influence of the screen type on the intensity of the following complaints: redness, lacrimation, piercing, sensitivity to light, and burning (Table 8). Mean intensities of burning, lacrimation, sensitivity to light, and piercing (see Figure 6) were bigger for the LCD TFT screen than for the CRT screen (significance level $< .05$).

TABLE 7. Mean Intensities of Asthenopic Symptoms

Complaints	LCD TFT Screen 1	LCD TFT Screen 2	LCD TFT Screen 3	CRT Screen 1	CRT Screen 2	CRT Screen 3
Redness	49.12	47.35	52.26	9.00	11.62	14.81
Sensitivity to light	28.52	26.22	33.53	16.30	16.66	20.80
Burning	21.80	27.50	23.86	10.63	16.10	18.13
Heaviness of eyelids	25.78	21.19	21.61	17.70	14.80	20.43
Lacrimation	14.86	24.75	23.55	6.23	5.56	9.63
Blurring	19.03	18.03	19.22	17.26	11.53	14.46
Sore eyes	19.97	13.83	14.44	11.36	13.56	14.43
Piercing	12.60	10.22	17.25	4.76	5.50	10.66
Itching	11.53	8.61	9.47	5.46	5.06	8.36
Double vision	7.00	2.83	5.72	1.60	5.53	2.66
Gritty feeling	6.44	7.42	7.39	4.63	6.70	6.43

Notes. LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; 1, 2, 3—lighting conditions.

TABLE 8. MANOVA Analysis of Asthenopic Symptoms Intensities. Main Effects: A—Type of Screen, B—Lighting Conditions

Symptoms	Main Effects	MANOVA	
		F(*df*)	Significance level
Lacrimation	A	16.167 (1, 192)	.0001
	B	1.255 (2, 192)	.2874
Burning	A	8.041 (1, 194)	.0051
	B	1.139 (2, 194)	.3222
Piercing	A	5.278 (1, 191)	.0227
	B	1.898 (2, 191)	.1526
Sensitivity to light	A	8.447 (1, 194)	.0041
	B	0.835 (2, 194)	.4356
Redness	A	4.386 (1, 178)	.0377
	B	1.509 (2, 178)	.2240

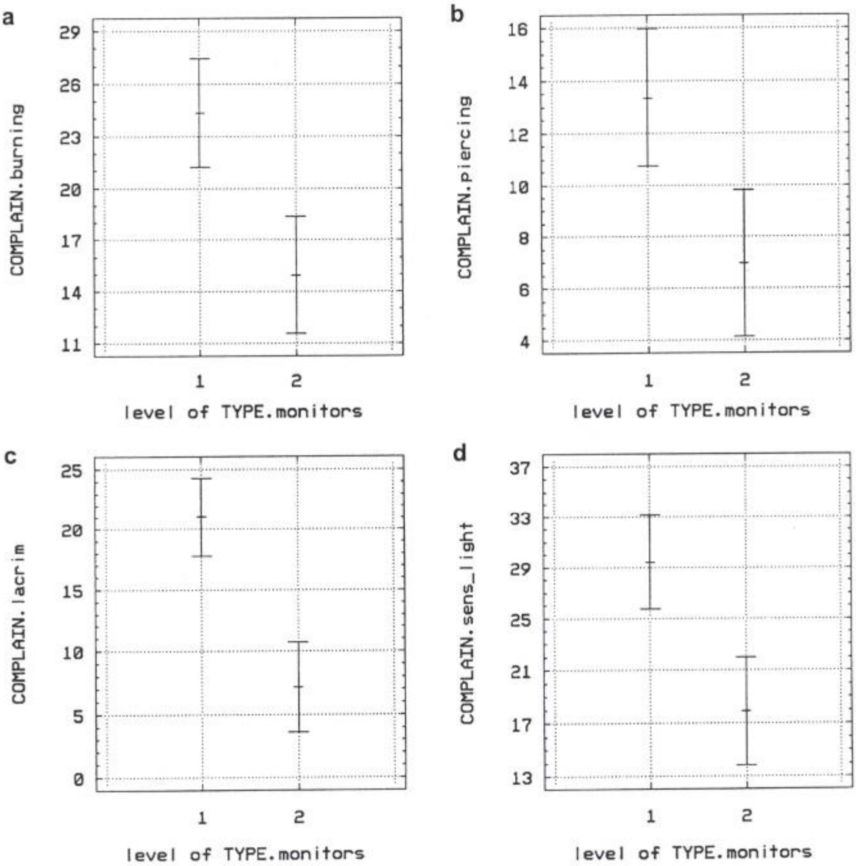


Figure 6. MANOVA—95% LSD intervals for factor means for intensities of (a) burning, (b) piercing, (c) lacrimation, (d) sensitivity to light. *Notes.* 1—LCD TFT screen, 2—CRT screen.

The most frequently reported problems were burning, sensitivity to light, and heaviness of eyelids (see Table 9). MANOVA analysis showed that there was a statistically significant influence of the screen type on the frequency of the following complaints:

- redness—significance level = .0029, $F(1, 2) = 32.64$,
- lacrimation—significance level = .0015, $F(1, 2) = 676.0$,
- gritty feeling—significance level = .0356, $F(1, 2) = 26.58$, and
- double vision—significance level = .0492, $F(1, 2) = 18.83$.

TABLE 9. Frequency of Asthenopic Symptoms

	Number of Participants, %					
	LCD TFT Screen			CRT Screen		
Complaints	1	2	3	1	2	3
Redness	45.5	47.1	54.5	60.0	63.0	63.0
Sensitivity to light	80.6	86.2	80.6	46.7	60.0	84.0
Burning	82.2	83.4	75.0	57.0	73.4	76.7
Heaviness of eyelids	75.0	69.5	75.0	66.7	66.7	53.4
Lacrimation	63.6	66.7	66.7	30.0	36.7	36.7
Blurring	58.4	72.3	66.7	60.0	60.0	63.4
Sore eyes	72.3	61.2	63.9	57.0	46.7	66.7
Piercing	60.0	50.0	66.7	30.0	33.4	40.0
Itching	61.2	66.7	50.0	46.7	33.4	36.7
Double vision	33.7	36.2	36.2	13.4	26.6	13.4
Gritty feeling	42.0	50.0	39.0	26.7	23.4	23.4

Notes. LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; 1, 2, 3—lighting conditions.

TABLE 10. Evaluation of Wall Behind the Display Brightness

	Number of Participants, %					
	LCD TFT Screen			CRT Screen		
Impression	1	2	3	1	2	3
Too bright	5.5	11.0	28.0	0.0	20.0	30.0
Slightly too bright	22.0	58.0	44.0	23.5	36.5	57.0
Appropriate	56.0	28.0	25.0	40.0	23.5	10.0
Slightly too dark	11.0	3.0	3.0	33.5	17.0	3.0
Too dark	5.5	0.0	0.0	3.0	3.0	0.0

Notes. LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; 1, 2, 3—lighting conditions.

Participants assessed their impression of the brightness of the wall behind the display (i.e., brightness of the surround) in all lighting variants. They had to mark one of the five possible answers, which corresponded to their impression of the wall brightness: *too bright, slightly too bright, appropriate, slightly too dark, too dark* (Table 10). The number of participants who assessed brightness of the surround as too bright increased with the value of surrounding luminance.

4.2. Changes in Visual Functions

4.2.1. Visual acuity

Table 11 shows changes in visual acuity (VA) for both screens upon different luminance of the surround values. The number of eyes in which VA (decimal notation) decreased from 1.5 to 1.0 and from 1.0 to 0.9 or 0.8 after the experimental session increased with the surrounding luminance for the LCD TFT screen only. No changes in VA in decimal notation were observed for the CRT screen. MANOVA analysis did not reveal any statistical influence of either the type of screen or lighting conditions on visual acuity changes.

TABLE 11. Changes of Visual Acuity (Number of Eyes)

	LCD TFT Screen			CRT Screen		
Decrease of Visual Acuity	**1**	**2**	**3**	**1**	**2**	**3**
From 1.5 to 1.0	2	4	8	0	0	0
From 1.0 to 0.9	1	1	1	0	0	0
From 1.0 to 0.8	1	2	3	0	0	0
Total Number	**4**	**7**	**12**	**0**	**0**	**0**

Notes. LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; 1, 2, 3—lighting conditions.

4.2.2. Amplitude of accommodation

Changes of the amplitude of accommodation were obtained by subtracting "after-before" values for each participant. Those changes were statistically analysed.

The reduction of the accommodation amplitude increased with the luminance of the surrounds (Table 12). MANOVA analysis revealed that there was a statistically significant influence of the surrounding luminance value on the accommodation changes—significance level = .0046, $F(2, 392) = 5.447$—and there was no significant influence of the type of screen—significance level = .189, $F(1, 392) = 1.729$. For both types of screen, the biggest changes in accommodation (about 1 Dptr) were found in the experiment with the luminance of the surrounds of 602 cd/m^2 (lighting conditions 3). They were significantly bigger than in the experiment with the luminance value of 45 and 205 cd/m^2 (lighting conditions 1 and 2) for both screens (see Figure 7a). However, no significant differences of the accommodation amplitude reduction between the screens were found, but slightly bigger changes for the CRT were observed (see Figure 7b).

TABLE 12. Changes in Accommodation Amplitude

	Means (*SD*), Dptr					
	LCD TFT Screen			CRT Screen		
Eyes	**1**	**2**	**3**	**1**	**2**	**3**
Right	−0.34 (1.37)	−0.54 (1.29)	−0.80 (1.73)	−0.47* (1.22)	−0.57 (1.10)	−1.12* (1.32)
Left	−0.23* (1.33)	−0.68 (0.98)	−0.93* (1.37)	−0.69 (1.41)	−0.65 (1.20)	−0.96 (1.27)
Right + Left	−0.28* (1.34)	−0.61 (1.14)	−0.86* (1.55)	−0.58* (1.31)	−0.61 (1.14)	−1.04* (1.29)

Notes. *—a statistically significant difference between experiment 1 and experiment 3; LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; 1, 2, 3—lighting conditions.

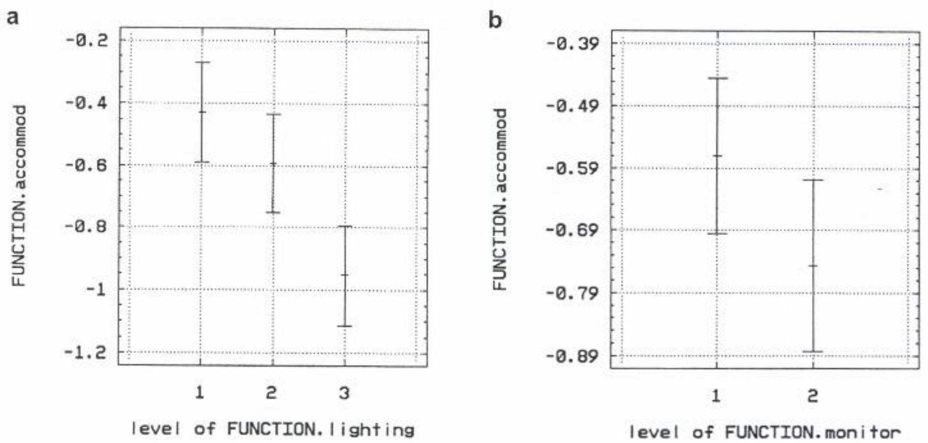


Figure 7. MANOVA—95% LSD intervals for factor means of accommodation amplitude changes: (a) between lighting conditions, (b) between screens. *Notes.* 1—LCD TFT screen, 2—CRT screen.

Gunnarson and Soderberg (1983) found a decrease in the near point of accommodation after strenuous VDT work but those changes were accompanied by increases in the subjective symptoms of visual discomfort, which did not occur in the present study.

4.2.3. Convergence

Table 13 shows the mean changes of the near point of convergence (NPC) with respect to lighting conditions and type of screen.

TABLE 13. Changes of the Convergence

	LCD TFT Screen			CRT Screen		
NPC Changes	**1**	**2**	**3**	**1**	**2**	**3**
Mean (*SD*), cm	1.14 (2.14)	0.84 (1.24)	1.37 (2.52)	0.81 (1.85)	1.64 (2.01)	1.42 (1.45)

Notes. NPC—near point of convergence; LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; 1, 2, 3—lighting conditions.

A reduction in the NPC after working with VDT was observed in all experiments. These changes of the NPC were also not significantly different between the two screens or between the different values of surrounding luminance. According to MANOVA analysis, convergence changes slightly increasing with growing surrounding luminance value can be observed (Figure 8).

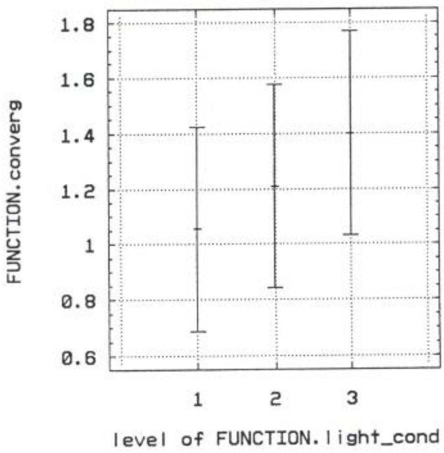


Figure 8. MANOVA—95% LSD intervals for factor means of convergence changes (between lighting conditions).

These results are supported by the results of Gunnarson and Soderberg (1983), who reported an increase in the near point of convergence (i.e., a reduced ability to converge) after VDT work (Megaw, 1995).

4.2.4. Horizontal near phoria

Two cases of phoria changes were separately analysed statistically: a comparison of the mean changes with their direction (esophoria "−" and exophoria "+") taken and not taken into consideration (absolute values of changes). Table 14 presents mean changes of near phoria. No statistically significant differences of near phoria changes were found. No consistent pattern of change in near phoria was found in either considered case. It was only established that work with VDT affected (in most cases) changes of phoria for near in the direction of esophoria (a minus sign before the mean value) irrespective of the type of screen or the surrounding luminance value.

TABLE 14. Changes of Horizontal Near Phoria

Changes of Near Phoria	Means (*SD*), Dptr					
	LCD TFT Screen			CRT Screen		
	1	2	3	1	2	3
Changes of direction considered	−1.01 (2.16)	−0.96 (2.51)	−1.50 (2.31)	−0.70 (2.75)	−1.33 (2.06)	−0.64 (2.10)
Absolute values of changes	1.84 (1.49)	1.86 (1.91)	2.06 (1.51)	2.28 (1.63)	1.73 (1.72)	1.74 (1.30)

Notes. LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; 1, 2, 3—lighting conditions.

4.2.5. Horizontal distance phoria

Table 15 presents mean changes of distance phoria. MANOVA analysis showed that there was no influence of the surrounding luminance value for either type of screen on distance phoria. It revealed that changes of phoria for distance differed (significance level $< .05$) between lighting conditions 2 and 3 with the direction of phoria changes taken into consideration. It could be said that, like for near phoria, work with VDT affected (in most cases) changes of distance phoria in the direction of esophoria irrespective of the type of screen or the surrounding luminance value. The biggest changes of distance phoria were obtained for the biggest value of surrounding luminance for both screens. There was a tendency towards bigger changes in distance phoria with an increase of the surrounding luminance value, in the case of absolute values of changes (for both screens). There were no significant differences of those changes between the screens.

TABLE 15. Changes of Horizontal Distance Phoria

Changes of Distance Phoria	Means (*SD*), Dptr					
	LCD TFT Screen			CRT Screen		
	1	2	3	1	2	3
Changes of direction considered	−0.47 (0.87)	−0.31 (0.99)	−0.83 (1.22)	−0.52 (1.19)	−0.42 (1.50)	−0.78 (1.89)
Absolute values of changes	0.72 (0.67)	0.87 (0.55)	1.01 (1.07)	0.89 (0.93)	0.93 (1.34)	1.08 (1.74)

Notes. LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; 1, 2, 3—lighting conditions.

Some studies found changes in phoria after prolonged visual work and observed a trend towards esophoria (Stone, Clarke, & Slater, 1980). Marek, Noworol, Pieczonka-Osikowska, Przetacznik, & Karwowski (1988) have reported an increase in the instability of phorias as VDT work progressed (Megaw, 1995). Phoria changes in the direction of esophoria and instability of phorias were confirmed by results of the present study.

4.2.6. CFF

Evaluation of critical fusional frequency (CFF) consisted of two measured parameters: ascending and descending threshold. The measurements of CFF were done only for the LCD TFT screen. Table 16 shows mean changes (after-before) of descending and ascending thresholds of CFF for different surrounding luminance values.

There was a tendency towards increasing ascending threshold (a plus sign before the mean value) and decreasing descending threshold (a minus sign before the mean value) of CFF after the experimental session in all experiments. There was no statistically significant difference between

TABLE 16. Changes of CFF

Changes of CFF	Means (*SD*), Hz		
	1	2	3
Ascending threshold	0.42 (1.24)	0.46 (1.08)	0.12 (0.94)
Descending threshold	−0.46 (1.2)	−0.43 (0.93)	−0.75 (1.18)

Notes. CFF—critical fusional frequency; 1, 2, 3—lighting conditions.

changes of both thresholds of CFF for all experiments. However, the biggest decrease in descending threshold was observed under lighting conditions 3 (i.e., for the biggest value of environmental luminance). Similarly to changes in phoria, an instability of CFF changes was observed.

4.3. Visual Performance

Visual performance was evaluated on the basis of the number of mistakes and the time needed to perform the visual task. MANOVA analysis showed that there was no influence of surrounding luminance—significance level = .814, $F(2, 2) = 0.228$—and type of screen—significance level = .063, $F(1, 2) = 14.392$ on visual performance—expressed by number of mistakes. Table 17 shows that the mean time needed to perform the visual task was almost the same (about 2 hrs) for each experiment for both screens. The biggest mean number of mistakes (50 mistakes) was observed under lighting conditions 3 for the LCD TFT screen. Moreover, there was a trend towards a bigger number of mistakes for the LCD TFT than for the CRT screen.

TABLE 17. Visual Performance

Visual Performance	Means (*SD*)					
	LCD TFT Screen			CRT Screen		
	1	2	3	1	2	3
Time, min	125.3 (18.8)	123.1 (23.2)	124.2 (20.9)	123.6 (19.1)	120.3 (20.6)	124.5 (19.4)
Number of mistakes	45.1 (42.6)	42.8 (33.7)	50.3 (29.1)	34.9 (30.8)	35.9 (33.2)	33.2 (21.3)

Notes. LCD TFT—Liquid Crystal Display with Thin Film Transistor; CRT—Cathode Ray Tube; 1, 2, 3—lighting conditions.

5. DISCUSSION

Improper luminance ratio between the screen and the wall behind the screen is one of the factors that can significantly contribute to the level of visual fatigue during VDT work. In the case of strenuous VDT work, especially with negative polarity of the screen, it is important to achieve appropriate luminance ratios. Daylight, which can meaningfully influence the surrounding luminance value and, in fact, luminance ratios could be a problem. The subjective evaluation of the surfaces' brightness in the visual field at the studied real VDT workstations showed that this factor does not seem to be the cause of perceived discomfort. Results of the presented study in the area of asthenopic symptoms confirmed this conclusion. Work with VDT itself affected asthenopic symptoms regardless of the luminance of the surrounds. On the other hand, it was shown that intensities of some symptoms like lacrimation, burning, piercing, and sensitivity to light were significantly bigger for the LCD TFT than for the CRT screen. This could be affected by the different sizes of the screens: 10.5″ for LCD TFT and 14″ for CRT (in 1995, when the study was begun the longest available diagonal of a stationary LCD screen was 10.5″). So, there could be two reasons for those differences: different character size and different size of the peripherally perceived visual field filled with the bright wall behind the display (i.e., surrounding luminance contribution). The tendency towards bigger visual problems during work with a flat panel screen (compared with a CRT screen) observed in our study is confirmed by other studies (Saito, 1997; Saito, Miyao, Kondo, Sakakibara, & Toyoshima, 1997), which stated that subjective complaints among flat panel users were greater than among CRT users.

In the present study, the brightness of the wall behind the display in the case of 602 cd/m^2 was assessed as too bright by approximately 30% of the participants, for both screens. On the basis of this example it could be said that for about 30% of the participants the surrounding luminance value of about 600 cd/m^2 can be the cause of discomfort glare. It is confirmed by the statement that "luminance of glare source must be greater than 500 to 700 cd/m^2 for discomfort glare to exist" (Publication CIE No. 55:1983; International Commission on Illumination [CIE], 1983). For 11 (LCD TFT) to 20% (CRT) of the participants the luminance of the wall of 205 cd/m^2 was too bright, and could be a cause of discomfort glare, too, especially in the case of negative polarity of the screen, which produces too extreme contrasts in space.

However, none of the participants stated a feeling of discomfort or irritation because of the brightness of the wall behind the display.

Objective measurements of changes of the visual functions, contrary to asthenopic symptoms, showed an influence of the surrounding luminance value on visual fatigue and lack of significant differences between screens (except for visual acuity). The obtained results of accommodation, distant phoria, and visual acuity indicated a tendency of visual fatigue to increase with the growing value of surrounding luminance (not significant except for a near point of accommodation). For both screens the changes of all monitored visual functions for lighting conditions with surrounding luminance of 45 and 205 cd/m^2 (luminance ratio of approximately 1:13 and 1:60, respectively) were approximately the same. Bigger (and, in the case of accommodation, statistically significant) differences were found between lighting conditions 1 (with surrounding luminance of 45 cd/m^2) and lighting conditions 3 (602 cd/m^2), and between lighting conditions 2 (205 cd/m^2) and lighting conditions 3. Therefore, accommodation seems to be a visual function most sensitive to changes of luminance distribution. On the basis of such results, it could be said that surrounding luminances values of less than 200 cd/m^2 (luminance ratio of less than 1:60) did not affect the growth of visual fatigue and drop in visual performance. Recorded results in the range of luminance ratio up to 1:60 confirmed the ISO (Standard No. ISO 9241-3:1992; ISO, 1992) luminance balance requirement that “for stationary visual field a significantly higher than 1:10 ratio of mean luminances between task area and its surrounds should not have any adverse effect.” But obtained data did not confirm another statement that for luminance ratio of 1:100 there could be a small but significant drop in performance, because for luminance ratio of 1:170 such a drop did not exist. Visual performance does not seem to depend on the value of surrounding luminance during 2 hrs of continuous VDT work.

Some differences in visual functions (visual acuity, distance phoria) between lighting conditions were statistically assessed as close to the significance border of .05. Probably longer VDT work (about 3–4 hrs) could affect bigger changes that would be considered significant.

6. CONCLUSIONS

Generally, very high luminance ratios (much bigger than 1:100) can affect the growth of visual fatigue, which (in some cases, especially for negative polarity screens) can accompany discomfort glare. Therefore, for prolonged and strenuous VDT work, both luminance ratios smaller than 1:60 and breaks for a rest (10–15 min after every 2 hrs of work) should be ensured. For casual VDT work, bigger than 1:60 luminance ratios should not have any significant influence on visual fatigue.

Results of the present study showed that there was no significant influence of the luminance ratio value on asthenopic symptoms for either type of screen and there was significant influence of the type of screen on those symptoms.

The measurements of changes of the visual functions, contrary to asthenopic symptoms, showed an influence of the surrounding luminance value on visual fatigue and lack of significant differences between screens.

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