Temporary blinding from bright light sources as a significant impact on occupational safety and health

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Abstract. Low power laser and high-brightness LEDs (HB-LEDs) have been applied in specially developed and computer assisted test setups in order to determine the duration and progression of colours in afterimages, the disturbance of visual acuity as well as the impairment of colour and contrast vision. Interrelationships between wavelength, exposure duration, optical power and energy have been investigated. Afterimage durations up to 300 seconds were found if the fovea of the human retina is irradiated from a laser beam at less than 30 µW, whereas lower values are valid in the parafoveal region and in the periphery. The visual acuity was strongly reduced during about 30 % of the afterimage time. The time-dependent progression of the afterimage colours was determined for 4 different dominant wavelengths of HB-LEDs, i.e. 455 nm, 530 nm, 590 nm and 625 nm, in the power range between 0.05 mW and 0.5 mW for exposure durations between 0.5 s and 5 s. The flight of colours obtained with 5 test persons is given as 8-bit RGB-values and illustrated as a function of the applied optical energy in the CIE chromaticity diagram together with the respective total afterimage durations. The colour contrast capability was investigated for 3 volunteers with specially developed test charts in 7 colours, namely without and after glare from 4 coloured high-brightness LEDs. Each subject completed 56 time-consuming tests since adequate adaptation was necessary between the respective tests. Glare increases the identification times about 14 s and 16 s and even stronger impairment is observable especially at low colour contrast. Tests with 40 subjects and 4 different pseudoisochromatic colour plates have shown that colour vision was impaired for periods between 27 s and 186 s depending on the applied colour plate and respective LED colour. Such relatively long lasting visual disturbances could be of particular concern connected with performing safety critical operations such as working with machines or at height, with high voltages or driving a vehicle or an airplane.

KEYWORDS: Glare, temporary blinding, high-brightness LEDs, visual acuity, colour contrast.

1. Introduction

The EU Directive 2006/25/EC lays down the minimum health and safety requirements for protection of workers from risks arising from exposure to artificial optical radiation [1]. According to this directive the employer has to determine the exposure at the workplace and the respective values have to be below the specified exposure limit values (ELVs), which are based on various ICNIRP (International Commission on Non-Ionizing Radiation) guidelines. In addition, he shall give particular attention to any indirect effects amongst others such as temporary blinding, when carrying out the risk assessment.

Since modern light sources like laser and high-brightness light emitting diodes (HB-LEDs) gain increasingly more applications not only harmful radiation might become accessible at work and for the general public, but in addition temporary blinding from these bright light sources might cause indirect effects, which may have general safety implications. Up to now secondary effects like temporary blinding have not been regarded in safety standards and there exist but a few data on this topic as far as modern artificial high intensity light sources are concerned.

Concerning especially illumination at the workplace the capability to be able to have a good vision on objects in the field of view is an important necessity especially for occupational health and safety and should be impaired as little as possible by modern light sources during various kinds of visual tasks.

Normally people can adapt to changing luminous conditions and perform well regardless of the illumination level, but glare might impair visual functions strongly and with a lasting effect, due to the fact that the adaptation system is overridden and an afterimage is formed.

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In order to get more reliable quantitative data concerning the influence of glare, dazzle, flash-blindness and afterimages it was the goal of a research project to investigate the various parameters which mainly determine the respective impact on vision. Therefore a low power laser and various HB-LEDs have been applied in specially designed and computer assisted test setups in order to determine the duration and progression of colours in afterimages, the disturbance of visual acuity as well as the impairment of colour and contrast vision as a function of the applied wavelength, optical power and exposure duration.

2. Methods

Since it was the purpose to identify not only miscellaneous qualitative effects arising from an exposure by means of a bright light source but to determine the respective quantitative impact on various vision capabilities, several test setups have been developed and applied in different studies with volunteers.

2.1 Spatial dependency of afterimages

Due to the fact that the accessible emission limits (AEL) of Class 1 laser products and the maximum permissible exposure (MPE) values have been increased it is mentioned now in the 2nd edition of the international standard IEC 60825-1 [2] in the description of this laser class that intrabeam viewing may produce dazzling visual effects, particularly in low ambient light, if the radiation is in the visible part of the spectrum. This might be regarded as an appropriate a step in the right direction, but only for Class 2 and 2M laser products, some additional information is available. For this case the standard states that indirect general safety implications might result from temporary disturbance of vision or from startle reactions.

Only sparse quantitative data are available with regard to the dazzling effects arising from visible emission of Class 1 laser products up to now. In particular the dependency on the angle between the line of sight and the beam direction has not been investigated, but due to the fact that the retina exhibits variable sensitivity, a spatial dependency of the duration of an afterimage was expected as far as the site of laser spot is regarded.

Since a well-collimated laser beam is particularly suitable for such an investigation, a helium-neon laser (wavelength 632.8 nm) was mounted on a movable assembly where the respective beam direction relative to the line of sight could be adjusted. In addition the mount could be inclined in a vertical plane. A detailed description of the measurement setup is given elsewhere [3]. The power was adjusted in several steps in order to investigate the respective dependence of the afterimage and restricted via a neutral density filter well below the accessible emission limits (AEL) of class 1 according to IEC 60825-1 [2]. Due to the fact that volunteers perceived an optical power of 39 µW as uncomfortably bright the applied power was restricted to 30 µW.

Measurements of the afterimage duration have been done between -40 degrees nasally and +60 degrees temporally for exposure durations of 1 s, 5 s, and 10 s, respectively. After the angular dependency has been determined in the range of 100 degrees the afterimage duration was measured at a fixed angle of 5 degrees temporally at 5 µW, 10 µW, 20 µW, and 30 µW.

Special notice was given to the foveal pit, which is the center of the macula and has a diameter of about 1.0 mm. This site is associated with the highest concentration of cone photoreceptors. In addition the position of the blind spot, which is the place lacking photoreceptor cells, but instead let pass the optic nerve through the retina, was carefully identified. The investigations were relatively time consuming due to the fact that sufficient re-adaptation time was necessary after each exposure in order not to falsify the results due to an interfering residual afterimage. The trials have been done with a total of 10 volunteers in the laboratory. The moment when the afterimage disappeared and could not be retrieved not even by squinting was taken as stop criterion for the determination of the duration of the afterimage.

In addition to the determination of physiological results given by the appearance of an afterimage, laser beam irradiations have been done between -60 degrees nasally to +110 degrees temporally in order to estimate the grade of psychological discomfort glare during the irradiation.

2.2 Determination of the flight of colours

If a dark-adapted eye is stimulated by a more or less brief exposure of a bright light, a sequence of afterimages of different colours follows, especially in dark-adapted eyes. This appearance is called the flight of colours. It normally can be demonstrated by adapting one's eyes in the dark, then switching on a bright light, fixating it with a steady gaze for a few seconds, turning the light off, and keeping the eyes as steady as possible.

Investigations have been done with high-brightness LEDs in order to determine the flight of colours for these high-intensity light sources. By simply glancing into such a device for time durations of less than 10 seconds a long-lasting afterimage that slowly changes colours was observed. A computer assisted measuring system was developed in order to determine the dependency on various parameters like colour, optical power and exposure duration of the stimulating LED. For that a specially designed colour wheel diagram has been designed and used which contains the necessary information on hue, saturation, and brightness. The time-dependent process and changes of the afterimage colours were determined for 4 different dominant wavelengths, i.e. 455 nm, 530 nm, 590 nm and 625 nm, in the optical power range between 0.05 mW and 0.5 mW for exposure durations between 0.5 s and 5 s.

A detailed description of the applied principle of measurement has been published elsewhere [4]. In order to be able to register the flight of colours sufficiently precise various configurations and arrangements have been tested in pilot studies until finally the illustration described in [4] has been chosen as an appropriate solution. The applied quasi continuous colour diagram consisted of 200 radial steps with a decrease of 0.4 % in brightness per step towards the centre and 198 steps in azimuthally direction, whereas 10 radial steps with a brightness decrease of 7 % have been used together with 24 azimuthally steps in order to illustrate the discrete colour circle.

Instead of performing the measurements in a dark room a special apparatus, consisting of two tubes, i.e. one with the stimulating HB-LED at the end and the other pointing onto the colour wheel at a distance of 30 cm, has been constructed which simultaneously restricted the amount of light entering the non-irradiated eye to a minimum. The perceived colour of the afterimage was recorded with an especially developed program written in LabView. The subjects assigned the perceived colours in the course of its chronological sequence via mouse click on an 8-bit colour diagram displayed on a computer monitor and the respective RGB values were recorded. The progression of the afterimage colours as a function of the applied optical energy was illustrated in the CIE chromaticity diagram together with the respective total afterimage duration. A total of 5 test persons took part in this special investigation.

2.3 Colour contrast capability after glare from HB-LEDs

In order to determine the quantitative effects after a temporary blinding glare from HB-LEDs a procedure has been developed where the test charts were based on the so-called Pelli-Robson contrast sensitivity chart but instead of Sloan letters coloured Landolt C-rings were used for the first time to our knowledge as optotypes to investigate contrast impairment, i.e. influence on colour and contrast visibility. The respective Landolt C-rings were arranged in groups of three each with the same primary colour and contrast value and successive groups decreased in contrast by a factor of $1/\sqrt{2}$ between 11 % and 1 %, i.e. 11.0 %, 7.9 %, 5.6 %, 4.0 %, 2.8 %, 2.0 %, 1.4 % and 1,0 %. There were 4 rows with 6 rings and randomized orientations of the gap in the ring. Since there were no appropriate colour contrast charts commercially available, the respective test charts have been produced on the basis of our own conception and specifications. Photoshop was used in TIFF-format. The typographic realization demanded some skill therefore and various prints were necessary in order to achieve the required Weber contrast values and grading.

The low contrast capability was investigated in a time-consuming trial with 3 volunteers with test charts in 7 colours, i.e. red, green, blue, cyan, magenta, yellow, and black as a reference. All measurements were performed under accurately defined and constant D65 illumination, which corresponds to daylight under special colour temperature conditions, namely without and after glare from 4 coloured LEDs, i.e. each subject completed 56 tests in order to check especially the ability to discriminate low contrast.

The subject's eye was at a distance of 10 cm from the aperture during the irradiation. Upon completion he/she stood in front of the Landolt C-ring contrast charts, which were positioned at a distance of 3 m at the lab wall. The size of these test charts was 594 mm × 420 mm (A2 wide format), which corresponds to the expected perceived afterimage size according to Emmert's law. The time duration of less than 3 s to move from the irradiation apparatus to the respective test site was insignificant since it was less than the time needed to identify an object after glare. The mean luminance of the charts was 85 cd/m^2 and the illuminance about 310 lx.

In addition trials have been performed with 4 different pseudoisochromatic colour plates designed by Ishihara for colour vision. These plates have been used to determine temporary colour deficiencies after an exposure from a high-brightness LED. For this purpose 40 volunteers have been included in a laboratory test.

As light sources 4 bright HB-LEDs have been used, namely at 455 nm (royal blue), 520 nm (green), 593 nm (amber) and 638 nm (red). In order to get a sufficiently large blinding light source the respective LED was positioned in the focal point of a collimator and a collimated beam was achieved. The collimator simultaneously represented the virtual source. All exposures have been performed with only one single exposure duration of 5 s, particularly to restrict the number of tests per subject acceptable. The selected optical power behind the 7-mm aperture was limited to 4 mW, since not all color HB-LEDs were able to deliver higher outputs. According to the international standard IEC 60825-1: 2001-08 the maximum permissible power is 30.9 mW, if the LED is treated as an extended source under laser conditions, which is now no longer valid as far as standards are regarded, since LEDs are included from now on in the new standard IEC 62471 and treated as lamps in most cases [5].

The subjects belonged to lab employees and students and to the age group between 20 and 40 years, where usually normal contrast sensitivity exists. All subjects became tested concerning their colour vision and ametropes carried their eyeglasses or contact lenses during the tests.

3. Results

In order to get the requested information on temporary effects as a result of irradiation from laser and LED devices, different methods have been applied and various specific parameters were used. Since indirect effects like temporary blinding are based on biochemical and neuronal relations, they have to be determined with the aid of volunteers and the achieved impacts might be described physiologically and/or psychophysically as well taking into account an interindividual variability.

All participants have been provided with the essential information concerning the aim of the investigations and gave their written consent to take part in the respective trial. Since the internationally agreed exposure limit values were never exceeded as far as the particularly adjusted exposure values concerns, there was never a real existing risk of an adverse effect to the eyes of the subjects.

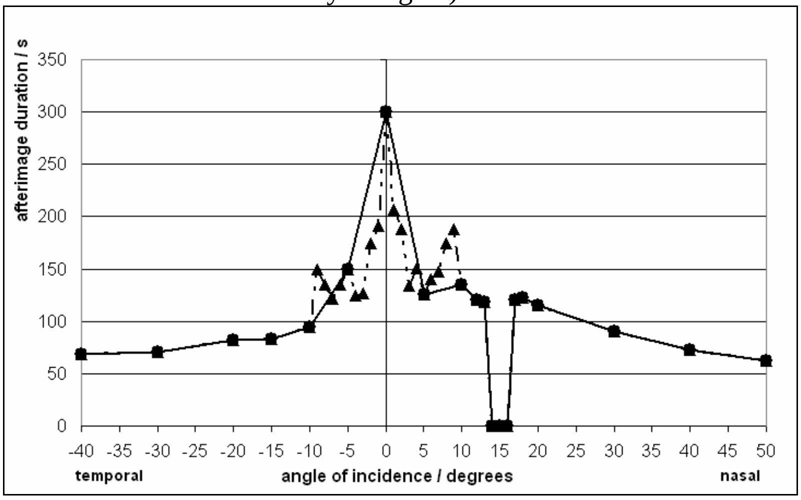
3.1 Spatial dependency of afterimages

The investigations have shown a strong dependence on the angle between the line of sight and the beam direction and in addition a dose-relationship holds concerning the duration of an afterimage as a function of exposure duration in the time interval between 0.5 s and 10 s.

Fig. 1 shows an example of the afterimage duration for a subject when the optical power of the applied laser was adjusted to P = 30 µW and the exposure duration was 10 s. Afterimage durations up to 300 seconds were found in this case if the fovea of the human retina is irradiated from a class 1 laser beam, that is to say when the optical power was less than 10 percent of the AEL (390 µW in the wavelength range between 500 nm and 700 nm) of class 1 according to IEC 60825-1, whereas much lower values are valid in the parafoveal region and in the periphery of the retina.

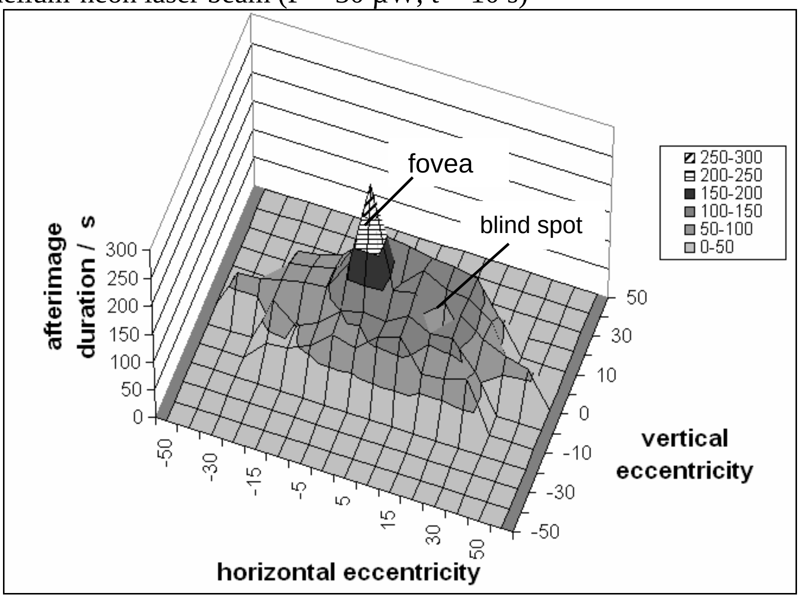
An even steeper curve is achieved in the foveal region if the measurement points according to the angle of incidence (glare angle) are taken to be separated by 1 degree only (dashed curve in Fig. 1). But it should not be ignored that it is not so easy to maintain such accuracy as far as the adjustment of the respective angle of incidence is concerned, although the head of the subject is well-positioned in a chin and front rest.

Figure 1: Afterimage duration as a function of the angle of incidence (glare angle). Exposure parameter: He:Ne-laser at 632.8 nm, P = 30 µW, t = 10 s (●, solid line: measurements every 5 degrees, ▲, dashed line: measurements every 1 degree)



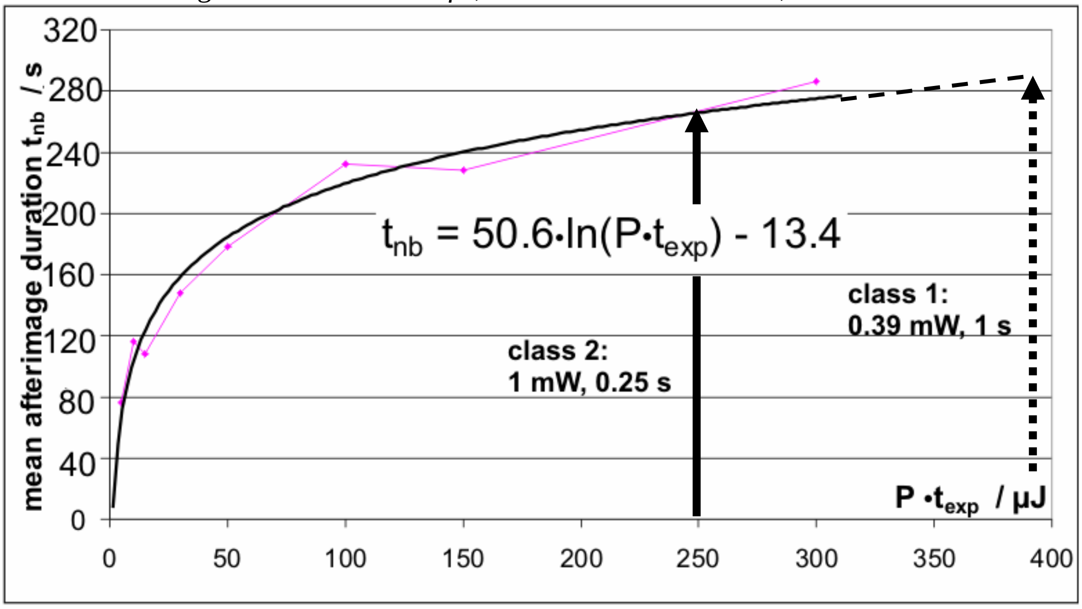
In addition to the determination of the afterimage duration in a line which goes through the fovea and the blind spot a two-dimensional distribution of the respective afterimage durations has been measured and is illustrated in Fig. 2. In this figure the particular location of the fovea and the blind spot (located at about 15 degrees nasally, shown in Fig. 1) is clearly depicted. The diagram in Fig. 1 might be taken from a cut through the two dimensional graph at a vertical eccentricity of 0 degrees.

Figure 2: Two dimensional distribution of the afterimage duration on the retina after an irradiation with a helium-neon laser beam (P = 30 µW, t = 10 s)



Last not least a functional interrelationship between the applied optical energy and the respective afterimage duration has been found, if the mean values of all measurements are displayed in Fig. 3.

Figure 3: Relationship between optical energy P•t_{exp} and afterimage duration t_{nb} (thin solid line: mean values of all measurements, thick solid line: expected interrelationship, dashed line: expected extension of the afterimage duration for >300 µJ, solid arrow: class 2 laser, dotted arrow: class 1 laser)



In order to draw this function the measurement results taken at a glare angle of 5 degrees nasally, which is equivalent to 5 degrees temporally according to the angle of incidence (cf. Fig. 1), have been doubled, since the afterimage duration lasts about twice as long in the fovea compared to a glare angle of 5 degrees laterally. The afterimage duration t_{nb} in seconds as a result of a laser beam exposure in the power range P between 5 µW and 30 µW and at exposure durations t_{exp} between 1 s and 10 s might be described as

$$t_{nb} = 50.6 \cdot \ln(P \cdot t_{exp}) - 13.4 \quad (1)$$

in the fovea. The afterimage duration as a function of the respective glare angle can be taken from Fig. 1, multiplying the values given in equation 1 by an angle dependent factor between 0 (equivalent to the blind spot) and 1 (equivalent to the fovea).

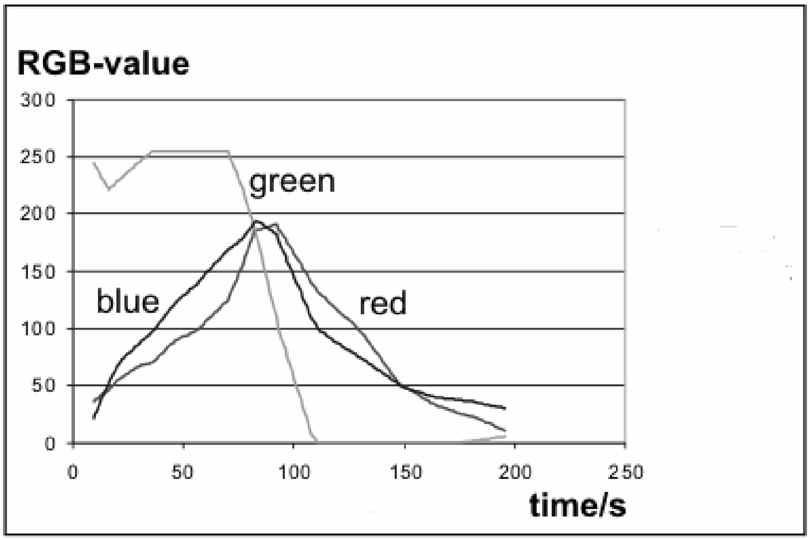
For comparison the expected afterimage duration for the case of irradiation from a class 2 laser (1 mW, 0.25 s) and from a class 1 laser (0.39 mW, 1 s) has been inserted into Fig. 3, although such an exposure has not been actually performed in the reported tests.

3.2 Flight of colours

The results obtained with 5 test persons have been recorded and especially the time course of the colour fractions is given in an 8-bit colour space with the respective RGB values. In order to illustrate the procedure which has been applied Fig. 4 shows an example of the time dependent RGB-values as a result of an exposure with an optical energy of 2.5 mJ (0.5 mW, 5 s) delivered from a green HB-LED (530 nm). The curves are obtained as mean values from 3 consecutive measurements with one subject, respectively. It has been shown that the individual difference is much less compared to the interindividual variance.

Similar results like the one shown in Fig. 4 have been obtained for the other three colors, i.e. 455 nm, 590 nm and 625 nm. For example in the case of stimulation with a red LED the curves for green and red are essentially interchanged and in addition the maxima for blue and green are shifted to earlier points in time. The variation of the total afterimage duration for the 5 subjects was considerably larger and covered a range between 70 s and 190 s, compared with green irradiation (170 s till 230 s), whereas blue LEDs yield durations between about 140 s and 170 s. In this later case there is a relatively large green content in RGB-values besides the expected blue during the first hundred seconds and when both contents decrease the red content starts to increase. Amber was associated with the lowest consistency in all measurements. Especially green has been perceived at a higher content compared to red during the first about 50 s after a stimulation with amber, but the green content declined earlier compared to red.

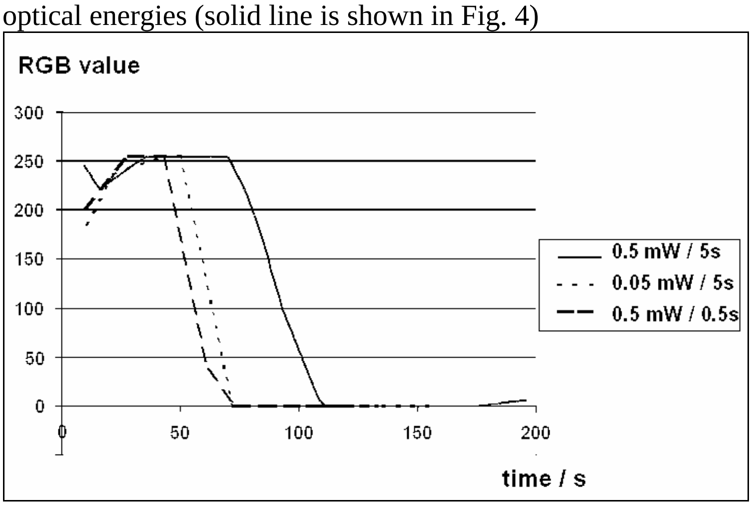
Figure 4: RGB-values as a function of time after exposure (blinding light source: HB-LED, 530 nm, 0.5 mW, 5 s)



All measurements in this part of the study have shown that the stimulating colour was dominant in the perception during the first, let's say, 50 s up to 100 s. Taken all results together a similarity in the perceived colours could be derived for all subjects, but an unambiguous progression of the colours of an afterimage does not exist as far as these investigations are concerned.

In order to estimate a dependency on optical power, exposure duration and/or optical energy measurements have been done both at the combinations of 0.05 mW and 5 s and 0.5 mW and 0.5 s, i.e. at 0.25 mJ, in addition to 2.5 mJ, as shown in Fig. 4. Fig. 5 shows the exclusive green content as a result of stimulation with a green LED, where a displacement of the curves between 30 s and 40 s might be seen for the lower optical energy compared to 2.5-mJ stimulation.

Figure 5: Characteristic curves of the green content after an irradiation with a green HB-LED at various optical energies (solid line is shown in Fig. 4)

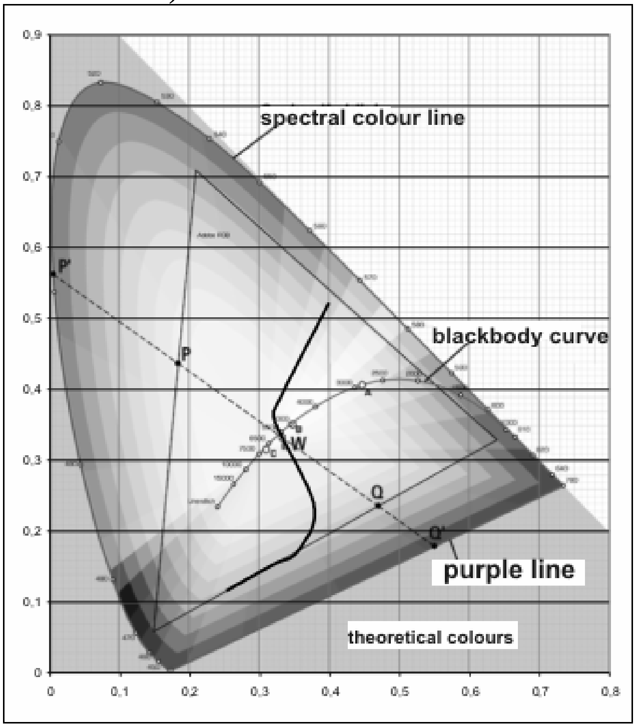


A much larger displacement of about 100 s was achieved if a red irradiation has been carried out. But in both cases the choice of parameters like exposure duration or optical power seems to be non-significant as far as the total energy is regarded.

A closer look at the flight of colours for all 5 subjects tested after irradiation with various HB-LED colours has been given in [4], where the respective perceived colours are illustrated.

The RGB-values as a function of time might be taken from Fig. 4 and can be displayed as a graph in a colour chromaticity diagram. This is shown in Fig. 6 for an optical energy of 0.25 mJ and a green HB-LED. The solid triangle in Fig. 6 shows the part of the colour diagram which can be shown on a monitor.

Figure 6: Trajectory of the progression of afterimage colours due to an irradiation with a green HB-LED, 0.25 mJ (0.5 mW / 0.5 s).



3.3 Colour contrast visibility

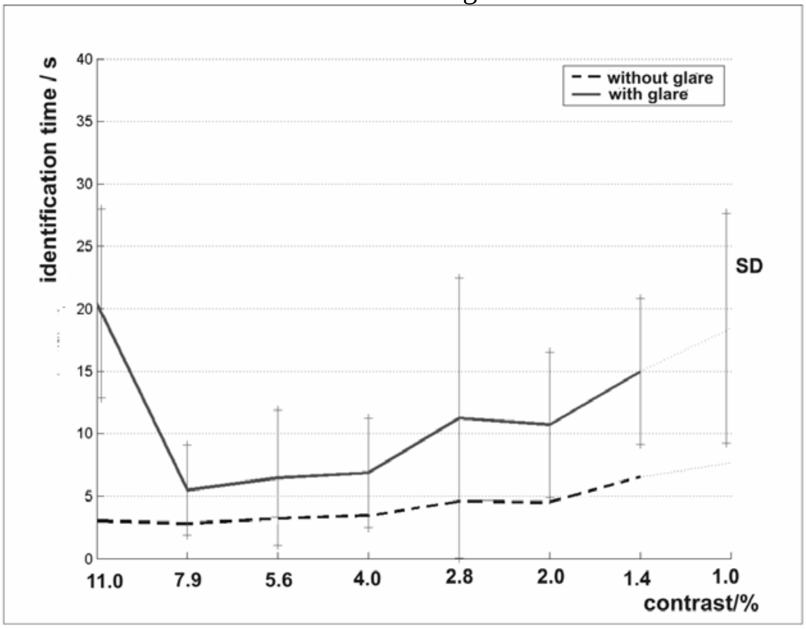
Tests with 4 differently coloured HB-LEDs have been performed with 6 coloured Landolt-C ring contrast charts and in addition a chart with black rings and with the same 8 contrast levels has been used as a reference. The results obtained from 3 subjects who took part in 56 tests were appropriately summarized. Fig. 7 shows the mean values together with the standard deviation (SD) for the times needed to identify the Landolt-C rings at various contrast values under normal conditions, i.e. without any glare, and after irradiation during 5 s with a coloured HB-LED.

As can be clearly seen from Fig. 7 there is a remarkable delay of about 18 s in order to identify the respective Landolt-C's with a contrast of 11 % due to temporary blinding compared with only 3 s, which are needed under normal vision conditions. Down to 4 % contrast the difference in identification time is less than about 3 s only, but increases up to about 8 s at lower contrast levels.

A comparison of the influence on the coloured and black Landolt C-rings has shown that perceptible deviations arise at less than 4 % contrast value. Finally glare results in a mean increase up to 16 s in identification time, which is 6 s more compared to black rings and about 10 s more compared to non glare conditions. For contrast values of only 1 %, no correct identification was possible under all test conditions.

Yellow has been excluded in Fig. 7 since for this colour the identification times were 35 s for 11 % contrast, 12 s for 7.9 %, 15 s for 5.6 %, 16 s for 4.0 % and 27 s for 2.8 %, and therefore the mean value would have been affected to strong by this colour. A contrast of 2 % could not be identified at all, if the Landolt C-rings were presented in yellow. Yellow has been found to be the colour which showed the largest individual differences for all 3 tested subjects.

Figure 7: Identification times without and after glare from a HB-LED



It was found that a contrast decrease of one level, i.e. a factor of $1/\sqrt{2}$, is equivalent to an increase of about 4 s in the required identification time and in addition a delay time between about 14 s and 16 s has been measured at the beginning of the respective test as a result of the dazzling glare from a HB-LED.

Concerning the colour of the applied LED the contrast vision is most disturbed after an irradiation from a green LED, but the difference to the other colours is relatively small, i.e. between 1 s at 5.6 % contrast and up to about 3 s at lower contrast values (more details are given in [6]). A fundamental relation between colour of the Landolt C-ring and the LED could not be derived from the achieved data, although the higher spectral visibility of the green LED seems to indicate a correlation between visibility, brightness and disturbance of colour contrast vision.

In extensive tests with a total of 40 subjects and 4 different Ishihara colour charts it was found that colour vision was impaired for periods between 27 s and 186 s depending on the applied colour plate and the respective LED colour.

4. Conclusion

Concerning the capability of Class-1 lasers to produce dazzle and glare it has been shown that the occurrence of relatively long lasting afterimages might interfere with visual functions up to 300 s as far as central vision is concerned and for at least half that duration if the beam incidence happens skew-angled. This has been found at an applied power which was only 10 % of the upper limit of class 1. Due to the accompanying discomfort perceived by the tested subjects it was not offhand to use higher optical power, especially for longer exposure durations. Therefore care should be taken not to produce long lasting temporary blinding with this laser class and the respective power levels.

The illustrated results achieved for a laser beam might not be transfered without any check-up to cases where the spot on the retina is much larger as in the case of a collimated laser beam, where the retinal diameter is between 25 µm and 50 µm, but some mean value interrelationship might be expected anyhow.

The results shown here fit well in the basics known up to now and extend the special consolidated findings. It is especially important to take note of the fact that not the complementary colour is dominating in the afterimage like is often stated in conventional literature on afterimage appearances, but the primary stimulating colour of the blinding light source and this is true during a comparatively long duration. Therefore the colour purity error might be deduced from the given progression of colours, namely during the first about 100 s.

The fact that the afterimage is perceived in the primary colour at first might be explained via the strength of the stimulus, i.e. the information of the colour of the stimulating bright light source is being transmitted to the brain or generated there for a while after the original stimulus has terminated. This impression is decreasing in intensity so that after specific time duration colours on the way to the respective complementary colour are perceived subsequently. Finally when the influence of the complementary colour is still further decreased the perceived colour of the afterimage often has a dark appearance of the final observed colour, like e.g. black blue or black green.

Different colour observations of the subjects might be explained partly by the individual colour perception, namely primarily as a result of slightly different photochemical reactions in the retina and in addition as a result of neuronal processes in the primary visual cortex. Besides that the physiological condition of the respective subject during the test might influence the capability to perceive colours. Even the physical and mental state on the day of testing might play a decisive role.

The investigations have shown that there exist some remarkable functional correlations, which might be applied in order to predict or to determine various impacts especially on visual acuity, colour and contrast vision. The influence of LED-irradiation on the capability to read is described elsewhere [3].

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REFERENCES

[1] DIRECTIVE 2006/25/EC OF THE EUROPEAN PARLIAMENT AND THE EUROPEAN COUNCIL of 5 April 2006 on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (ARTIFICIAL OPTICAL RADIATION) (19th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC), OJ L 114, 27.4.2006, p.38.

[2] INTERNATIONAL ELECTROTECHNICAL COMMISSION, IEC 60825-1: 1993 + A1:1997 + A2:2001, Safety of laser products – Part 1: Equipment classification, requirements and user's guide.
IEC 60825-1, Ed.2.0: 2007, Safety of laser products - Part 1: Equipment classification and requirements.

[3] REIDENBACH, H.-D., Local susceptibility of the retina, formation and duration of afterimages in the case of class 1 laser products and disability glare arising from HB-LEDs, Journal of Laser Applications, accepted for publication 2008.

[4] REIDENBACH H.-D., Determination of the time dependence of colored afterimages, In Ophthalmic Technologies XVIII. Edited by Manns, F.; Söderberg, P. G.; Ho, A.; Stuck, B. E.; Belkin, M. Proceedings of the SPIE, Volume 6844, pp. 68441N-68441N-9 (2008).

[5] INTERNATIONAL ELECTROTECHNICAL COMMISSION, IEC 62471 (CIE S 009:2002): 2006-07 Ed. 1.0, Photobiological safety of lamps and lamp systems.

[6] REIDENBACH H.-D., Color and contrast sensitivity after glare from high-brightness LEDs, In Ophthalmic Technologies XVIII. Edited by Manns, F.; Söderberg, P. G.; Ho, A.; Stuck, B. E.; Belkin, M. Proceedings of the SPIE, Volume 6844, pp. 68441R-68441R-8 (2008).