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D5.4 Exploration of safety issues in Eyetracking

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Executive Summary

This document describes the use of infra red light in eyetracking equipment, reviews current standards and guidelines regarding safe exposure to infra red light, and outlines the steps being taken by COGAIN to ensure the safety of both current and future hardware. The task was proposed by the Board of User Communities (BUC) in order to address safety concerns with regard to infra red light exposure. In the course of the review process, expert advise was sought from appropriate standardising bodies and the applicability of currently existing standards for long term daily exposure was brought into question. As a result of this, COGAIN and CIE members, including both academic and industrial partners, have initiated a Technical Committee within the CIE in order to develop a safety standard for eyetrackers. The first meeting of the proposed Technical Committee took place in November 2007, the outcomes of this meeting are referred to throughout the document.

The motivation is to address the lack of clarity in the standards literature as regards long-term daily exposure, in order to provide a clear safety protocol for developers and users alike. Several exposure guidelines currently exist, but the question has arisen as to whether the long-term nature of exposure for assistive devices falls outside the assumed conditions. This report considers the current state of optical radiation safety guidelines which may apply and considers what special precautions may be necessary in the case of eyetracking for communication. In light of the increasing use of eyetracking technology both for the physically disabled and for mainstream applications, the opportunity to bring together expertise from standardising bodies and from COGAIN in setting safe emission levels is timely and appropriate.

Chapter 1 outlines the kinds of lighting used in the various hardware configurations of eyetrackers. It also explains lighting characteristics which have a bearing on the calculation of safe emmission levels. Chapters 2-4 integrate the report commissioned by COGAIN of Dr. David Sliney, member of the CIE and the proposed chair of the Technical Committee which has resulted from this work, in order to review current standards. Hence this document represents the co-operation of COGAIN members with external international expertise. These chapters outline the possible hazards of exposure to infra red light, the safety standards currently in use, and the reasons for developing a standard more specific to eyetracking. Chapter 6 briefly outlines some possible considerations specific to users with physical disability which we feel should be included in the intended standard but will need the expertise of the Technical Committee members for further elaboration. Chapter 7 includes proposed outcomes in the form of information dissemination to users and to industry members.

In the course of work on this deliverable, a meeting of the members of the proposed Technical Committee was held. During this meeting, several commercial and prototype eyetracking systems were measured in order to investigate correct measurement procedures. Although we have included these measurements in the appendices, they should by no means be considered conclusive, and hence we do not specify which measures come from which systems. For our purposes, a margin of error in these measurements was acceptable so long as this margin did not include the possibility of a system even approaching maximum exposure levels. All of the systems we tested, albeit with limited equipment, were well within current safety levels. We offer this information as a guide to, but not an absolute value of, the range of light conditions in a broad selection of current hardware. Finally, we have included some supportive information in the appendices, namely definitions of terms and a comparative list of the calculations currently used in international standards. We intend that this information will promote a concerted effort from all sides towards a clear and workable standard.

1 EYETRACKING AND INFRA RED LIGHT

This section is a general description of the type of lighting employed in eyetrackers. Detailed information, i.e. specific values or ranges are not given since for many of the trackers this information is not publicly available.

1.1 Characteristics of light sources in eyetracking

Most gaze tracking systems use of infra red illumination (IR). Light is usually produced via IR light-emitting diodes (LEDs). There are two main justifications for the use of this type of lighting in eye-tracking systems:

a) The use of a light source in the scene enhances the quality of the image and facilitates detailed image analysis and gaze estimation.

b) Infra red light is not visible to the human eye, so the light is comfortable for the user and does not distract attention.

Infra red light is reflected by the corneal surface, creating reflection points which are projected to the image as bright pixels, termed ‘glints’ or corneal reflections (see Figure 1).

Figure 1. An eye image using two infrared light sources.

The glint positions are commonly used for gaze estimation purposes. It is frequently assumed that the position of the glint in the image changes not with eye rotations but with eyeball translations, thus giving a reference for head position. In more accurate approaches, this assumption is removed and the movement of the glint due to eyeball rotations is introduced in alternative models for gaze estimation [Shih & Liu, (2004); Guestrin & Eizenman, 2006).

On the other hand, using the appropriate lighting is essential in computer vision problems. Providing the appropriate lighting conditions improves image quality in terms of contrast and intensity levels and facilitates the image processing task. As previously mentioned, using light in the IR range is a non-intrusive method of providing the needed contrast in the image.

The following section provides additional details about the configurations and lighting conditions employed by various eye-tracking systems.

1.1.1 Head mounted versus remote eyetrackers

One of the most challenging problems for gaze estimation purposes is that of compensating for head movements. Head position in 3-D space affects gaze direction. For the same eyeball rotation with respect to the head the gaze point is different for different 3-D head positions.

One of the solutions to this problem is to use head mounted systems. In these systems, the eyetracker elements are placed in a helmet or in special glasses to which the lighting and additional hardware are attached. In this manner, reference to head position is not necessary since the system rotates and translates together with the skull.

We find head mounted systems (HMD) based on video-oculography such as the ones shown in Figure 2, and systems just based on infrared lighting and no cameras such as the OWL approach shown in Figure 3.

Figure 2. Eye-tracking Head Mounted Systems[1]

Figure 3. OWL system[2]

Remote gaze tracking systems reduce the intrusiveness to the user by placing the hardware, i.e. cameras and lighting, far from the user.

Video-oculography (VOG) remote gaze tracking systems are normally based on groups of IR light sources and a camera (see Figure 4). Systems based on time of flight (TOF) cameras can be considered as a special case since IR lighting and the camera are part of the same device (see Figure 5).

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[1] Applied Science Laboratory. Mobile eye, H6 Head Mounted, http://www.a-s-l.com/

[2] OWL http://www.redcedar.com/owlQandA.html

Figure 4. Remote VOG gaze tracking systems[3]

Figure 5. TOF camera[4]

In general, in standard configurations of remote eye-tracking systems, lights sources are placed close to the monitor gazed at by the user. We can assume a standard working distance from the camera between 400 to 600 mm.

When studying the effects of IR light on the eye we should take into account that in head mounted systems the LEDs are placed closer to the eye in comparison to remote eye-tracking systems.

1.1.2 On and Off axis lighting

The relative position of the eye-lighting-camera derives on different location for the glint in the image and can produce different effects. One of the most applied distinctions is to classify the IR light position as on axis and off axis (axis is referred to the optical axis of the camera). Thus, the light source can be placed coaxially to the camera or not coaxially to the camera (see Figure 6).

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[3] Tobii Technology http://www.tobii.com.
EyeTech Digital Systems (QuickGlance3) http://www.eyetechds.com/assistivetech/products/qg3.htm

[4] CSEM http://www.csem.ch/

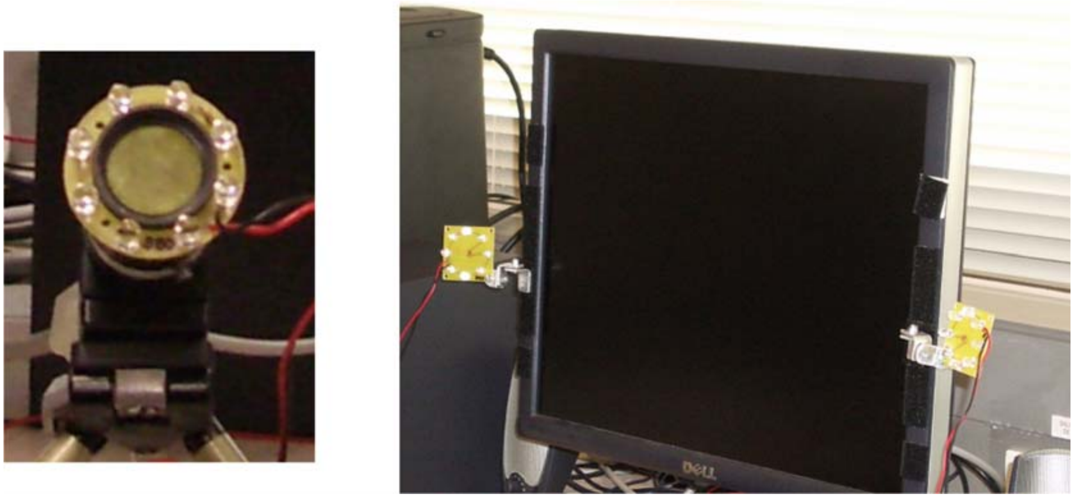

Figure 6. On axis / off axis lighting

Using on axis lighting effects both image processing and gaze estimation. With regards to the image, the most interesting effect of the on axis lighting is the bright pupil effect (see Figure 7). All the light reflected back by the retina reaches the camera making the pupil appear bright in the image. It is a similar effect to the red-eye effect in photography when the flash is located near to the lens. Since most eyetrackers work with B&W images, the pupil does not appear red but light grey. It is assumed that the bright pupil is more easily detected since the contrast with respect to the iris is increased; however, problems have been reported for light irises and for outdoor applications. The central location of the LEDs is also sometimes used for gaze estimation purposes (Yoo & Chung, 2005).

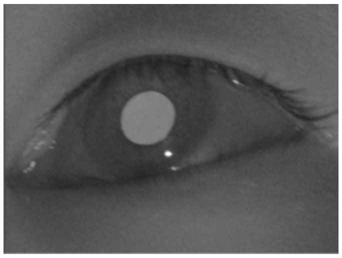

Figure 7. Bright pupil image[5]

Placing the light sources far from the camera axis eliminates the bright pupil effect making the pupil appear dark in the image (Figure 8).

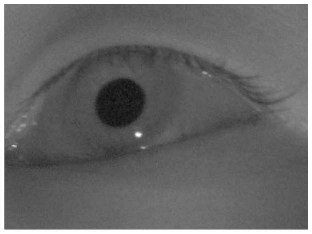

Figure 8. Dark pupil image[5]

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[5] IBM Almaden Research Center. http://www.almaden.ibm.com/

1.1.3 Single LED versus array

The light sources employed in eye-tracking can be composed of single LEDs or composed of array of LEDs arranged in various manners. The objective of using arrays of LEDs is to generate more powerful point sources and larger glints in the image, hence reducing the indetermination in computation of the glint position in the image (see Figure 9).

Figure 9. Single LED vs. Multiple LEDs sources

We cannot give exact numbers about the maximum number of LEDs used in eye-tracking systems, however, we can confirm that some systems use arrays of between 30 to 40 LEDs.

1.1.4 Use of lenses and filters

Additional hardware elements can be used to modify the effects of the IR light in eye-tracking systems. The use of lenses in front of the IR source can modify the light pattern. Some systems make use of lenses to increase the apparent size of the source. This will result in larger glints in the image and, consequently, lower indeterminations in the glint locations.

Some cameras filter out the visible light and capture just the image resulting from the IR emission. However, the filters do not affect the exposure of the eye to the light but the quality of the image to be analyzed.

1.2 Characteristics of emitted light in eye-tracking

In this section we describe additional aspects of the use of IR light in eye-tracking from the point of view of the characteristics of the emitted light. As mentioned before we cannot provide exact numbers or ranges, however, we would like to point out some of the most important aspects of the emitted light.

From the reported data we might say that the wavelengths used are in the near infrared range from 820 nm to 950 nm approximately. It is more difficult to give general numbers about the emission power, bandwidth etc.

1.2.1 Pulsed and continuous light

We can distinguish between continuous and pulsed light. The former maintain the light on continuously in the same condition during the tracking session. Contrarily, the latter switch the lights on and off using alternative synchronization patterns. The pulsing frequency varies from one system to the other and might have alternative objectives (not completely reported). Many of the systems present a frequency synchronized with the camera acquisition rate, so that they keep the lights on during part or the whole acquisition period of the image and switch the lights off until the next image starts to be acquired. There are cases in which different pulse frequencies are used for different point light sources.

Although the objectives of using pulsed lights have not been fully reported, it is generally assumed that pulsing infra red light at a given frequency enables easier differentiation between system and ambient infra red light and reflections.

1.2.2 Mixed lighting conditions

A particular case of pulsed light is the use of mixed light conditions. In these kind of systems on / off axis lights are combined in the same system with different lighting frequencies or using continuous light for off axis lighting and pulsed light for on axis lighting. Regardless of whether the light is on or off axis, the essential point of this technique is the use of pulsed light for the on axis light source. This is known as the image difference method. As mentioned before, on axis lighting creates a bright pupil effect in the image. Two consecutive frames or images of the eye are acquired, in one, the on axis lighting is on and in the next it is off. As mentioned before, the off axis lighting can be off during the on axis lighting or continuously on. Ideally, assuming that the eye movement between two consecutive frames is minimal, the most important difference between the images would be the intensity level of the pupil. In the first of the images we would have a bright pupil and in the second one a dark pupil. Then, calculating the difference between the two frames will result in an image in which the blob with the highest intensity, among the blobs greater than a specified size, is going to be the pupil area. In this manner, the pupil can be located easily in the image (Ebisawa, 1995).

2 POTENTIAL OPTICAL RADIATION HAZARDS

The eye is well adapted to protect itself against overly intense broad-band optical radiation (ultraviolet, visible and infrared radiant energy) from the natural environment and mankind has learned to use protective measures, such as hats and eye-protectors, to shield against the harmful effects upon the eye from very intense ultraviolet radiation (UVR) and blue light present in sunlight over snow or sand. The eye is also protected against bright light by the natural aversion response to viewing brightly visible light sources. The aversion response normally protects the eye against injury from viewing bright light sources such as the sun, arc lamps and welding arcs, since this aversion limits the duration of exposure to a fraction of a second (about 0.25 s).

The infrared LEDs employed in most infrared LED eyetrackers do not, however, produce a strong aversion response, as they are barely visible, and the spectral emission is limited to the near-infrared (IR-A, 780-1400 nm) spectral band. If a conventional incandescent lamp or discharge lamp that has been filtered to block most visible light and transmit IR-A is employed, some emissions of note are possible outside the IR-A and must be evaluated separately. In general, optical radiation safety guidelines identify at least five separate types of potential hazards to the eye from intense optical sources that normally have to be independently evaluated to assure optical safety (ACGIH, 1998).

(a) Ultraviolet photochemical injury to the cornea (photokeratitis) and lens (cataract) of the eye (180 nm to 400 nm): two criteria.

(b) Thermal injury to the retina of the eye (400 nm to 1400 nm).

(c) Blue-light photochemical injury to the retina of the eye; principally 400 nm to 550 nm; unless aphakic (condition in which the chrystaline lens of the eye is absent), 310 to 550 nm (ACGIH, 2007)

(d) Near-infrared thermal hazards to the lens (approximately 800 nm to 3000 nm).

(e) Thermal injury (burns) of the cornea of the eye (approximately 1400 nm to 1 mm).

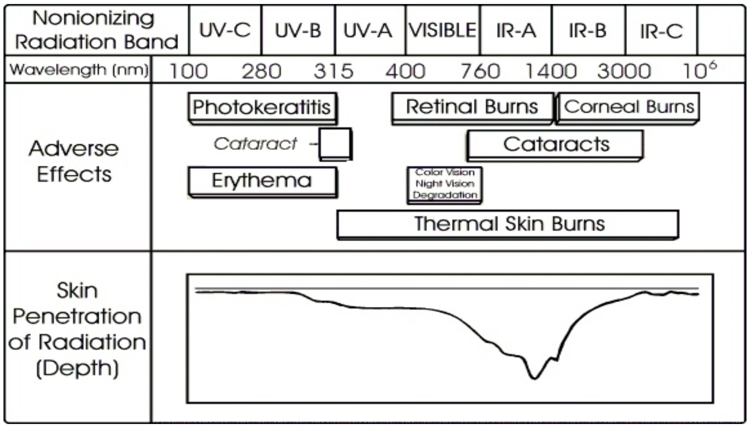

Figure 10. The different photobiological effects of optical radiation are generally limited to specific spectral bands. The photobiological bands of the International Commission on Illumination (CIE) are shown at the top. The hazard criteria listed in (a) through (e) above generally apply to only one or two spectral regions.

For the LEDs and IR-A filtered lamps used in most infrared eyetrackers, only aspects (b) and (d) are relevant. There should be no detectable ultraviolet or blue light from the LEDs and the emitted far-infrared (thermal) radiant energy is insignificant. The retinal thermal injury hazard (b) normally requires optical radiance values characteristic of intense xenon-arc lamps if visible light is present and the hazard criterion is limited to ten second exposures or less; however, in the case of a near-infrared source with a weak visual stimulus, special retinal thermal hazard criteria exist for continuous viewing. Therefore this *retinal thermal* effect (b) and the infrared hazard to the lens (d) should be evaluated in detail for each system. To prove beyond any doubt that UVR is of no concern, aspect (a) can also be quickly checked by measurement. Any blue light emission would be readily detectable (and annoyingly bright) if it were of concern in any system.

3 OPTICAL RADIATION SAFETY GUIDELINES AND STANDARDS

3.1 Hazard Criterion

Several national and international organizations provide guidelines for human exposure to optical radiation and recommend ***exposure limits*** for the eye and skin. The most prominent are the: American Conference of Governmental Industrial Hygienists (ACGIH)[1-2] in North America and the International Commission for Non-Ionizing Radiation Protection (ICNIRP, 1997). In the European Union, there is an Optical Radiation Directive that employs the ICNIRP exposure limits in the workplace. Other organizations recommend product-safety ***emission limits*** (ANSI, 2005, 2000, 2007; CIE, 2002; CENELEC, 2002; IEC, 2007; CDRH, 1995) Currently, there are only two sets of different types of **product** safety standards that apply to the use of lamps—including solid-state lamps (LED's) worldwide. These are:

3.1.1 The CIE Lamp Safety Standard

CIE Standard S009/E-2002, Photobiological Safety of Lamps and Lamp Systems, which was based upon an earlier edition of the American National Standard, ANSI RP-27.1-2005, *Recommended Practice for Photobiological Safety for Lamps and Lamps Systems: General Requirements,* published by the Illuminating Engineering Society of North America. These documents are the first in a series of standards, and employ ocular exposure limits that are essentially identical to the guidelines for human exposure published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), which, in turn, are essentially the same as the Threshold Limit Values (TLV's) for broadband optical radiation published by the American Conference of Governmental Industrial Hygienists (ACGIH). The ACGIH and ICNIRP differe slightly in the UV-A spectral region but not for visible radiation and near-infrared. Also, ICNIRP recommends that these guidelines for incoherent—and not laser light sources—be applied to LEDs. One of the IESNA (**Illuminating Engineering Society of North America)** standards included specific guidelines on methods of measurement at realistic viewing distances—not closer than 20 cm—that are not given by the ACGIH, but were adopted by the CIE S009.

3.1.2 The IEC/CIE Lamp Safety Standard

IEC 62471/CIES009-2006, Photobiological Safety of Lamps and Lamp Systems, which is identical to CIE S009/E-2002, but became a joint-logo standard in 2006. This provides guidance to manufacturers on the classification of lamps and lamp systems into one of four risk groups, but gives no requirements for labeling etc. A draft IEC technical report, *IEC TR 62471-2. Photobiological safety of lamps and lamp systems - Part 2: guidance on manufacturing requirements relating to non-laser optical radiation*, is currently a work-in-progress with potential completion and publication in 2008.

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3.1.3 The EN 60825-1 Laser Product Safety Standard

In Europe, a laser safety standard issued by CENELEC also applied until recently to LEDs: *EN 60825-1:1994 (+ corr. Feb. 1995) + A1:2002 + A2:2001 (+ corr. Apr. 2004) -- Amendment 2 to Safety of Laser Products - Part 1: Equipment Classification, Requirements, and Users' Guide*. This was based on *IEC 60825-1:1993 Safety of Laser Products - Part 1: Equipment Classification, Requirements, and Users' Guide*, the international laser product standard from the International Electrotechnical Commission (IEC). The inclusion of LEDs by IEC Technical Committee TC-76 (which developed the standard) in 1993 was largely to treat the specific use of infrared LEDs in optical fiber communication systems. The many different geometries of other LED products were not properly considered and subsequent amendments attempted to correct some of these problems in 1996 and 2001. Since national and international experts considered this application of laser limits to incoherent sources as **overly conservative**, the IEC TC76 voted to eliminate the inclusion of LEDs in the second edition of IEC 60825-1, which was published in March 2007. Although IEC 60825-1 no longer applies to the LEDs in eyetracker systems, IEC 62471:2006 does apply.

3.2 HUMAN EXPOSURE LIMITS FOR HAZARD EVALUATION

The ICNIRP recommended guidelines for limiting human exposure to optical radiation may be updated for the retinal thermal limits in the future—increasing them slightly. However, the following limits for ocular exposure to broadband visible and infrared radiation are currently recommended by ICNIRP for use when analyzing the potential optical radiation hazards to the retina from lamps and LEDs: ACGIH had issued a Notice of Intent to Change its limits (TLVs) in 2008.

3.2.1 Exposure Guidelines for IR-A Radiant Energy

Both ICNIRP and ACGIH provide exposure limits for near-infrared optical radiation. If the emitting areas of adjacent LED sources are separated by at least 100 milliradians (5.7 degrees), i.e., by 2 cm at the standard 20-cm assessment distance, then from the retinal hazard standpoint, they are considered completely independent. However, for the risk assessment to cornea and lens, they are all additive in the infrared band.

3.2.2 Infrared Corneal (Lens) Thermal Hazard

The ACGIH and ICNIRP recommend a maximal daily corneal exposure of 10 mW/cm^2 total irradiance for wavelengths 770-3,000 nm (E_{IR}-only) for day-long, continuous exposures, which could be applied to the sum of the average irradiance of all of the infrared LEDs is:

$$E_{IR\text{-}only} = 0.01\ \mathrm{W \cdot cm^{-2}} \quad \text{average for } t > 1{,}000\ \mathrm{s} \qquad [1]$$

The maximal measured irradiance at the reference worst-case viewing distance of 20 cm for any of the units tested in the first meeting of the Technical Committee in Brussels was 1000 µW/cm^2 (i.e., 1.0 mW/cm^2) for the units tested. It would not be possible for the eye to be exposed realistically to higher levels for lengthy periods. This is termed the "the infrared radiation hazard limit" in the ANSI/IESNA and CIE/IEC lamp safety standards.

Higher irradiances are permitted for exposure durations less than 1,000 s (~ 16.6 minutes):

$$E_{IR\text{-}only} = 1.8\ t^{-0.75}\ \mathrm{W \cdot cm^{-2}} \qquad [2]$$

$$= 210\ \mathrm{W{\cdot}cm^{-2}} \quad \text{as an example for a single 800-µs pulse,}$$

but since the peak irradiances would be only increased by the reciprocal of the duty-cycle, the peak irradiance may not be the limiting case. For systems using repetitively pulsed light, the peak power must also be evaluated.

3.2.3 Retinal Thermal Hazard

As would be expected from any infrared LED, there is no UV or blue-light hazard from the prototype device and the measurements of typical systems confirmed this. The CIE/IEC international standard IEC/CIE62471/S-009E-2006 and ANSI RP27.1-2006 lamp safety standards follow the ACGIH TLV (1998) and ICNIRP (1997) guideline to protect the human retina against the retinal thermal hazard as well as "the infrared lens hazard." The TLV is for lengthy viewing, i.e., for t > 1,000 s is:

$$L_{NIR} = \Sigma\, L_\lambda \cdot R(\lambda) \cdot \Delta\lambda \ \le\ 0.6/\alpha\ \ \mathrm{W{\cdot}cm^{-2}{\cdot}sr^{-1}} \qquad \text{for } t > 810\ \mathrm{s} \qquad [3]$$

$$\le\ 6.0\ \mathrm{W{\cdot}cm^{-2}{\cdot}sr^{-1}} \ \ \text{for } \alpha = 100\ \mathrm{mrad} = 0.1\ \text{radian}$$

where the value of R(λ) between 700 nm and 1100 nm is:

$$R(\lambda) = 10^{[(700\ \mathrm{nm} - \lambda)/500\ \mathrm{nm}]} \qquad [4]$$

which, for example, has a value of 0.60 for a wavelength of 810 nm, but since an 800-nm LED would typically have a 30-nm emission bandwidth (FWHM), it is customary to use the R(λ) value that applies at the shorter edge of the bandwidth measured at 50% if peak, i.e., at 795 nm, where R(λ) is 0.65. From Table B-1, the measured maximal values of L that were taken at the first TC meeting in Brussels were about 3.7 $\mathrm{W{\cdot}cm^{-2}{\cdot}sr^{-1}}$ or less. Thus, when the measured radiance is multiplied by the R(λ) factor, the effective radiance becomes, less. For example, $(0.066\ \mathrm{W{\cdot}cm^{-2}{\cdot}sr^{-1}}) \bullet (0.65) = 0.043\ \mathrm{W{\cdot}cm^{-2}{\cdot}sr^{-1}}$ effective, which is only about 0.6% of the limit for t > 810 s and even the peak radiance for a 0.8-ms pulse does not exceed the long-term, continuous exposure limit. The limiting radiance provided by ACGIH for t < 810 s and all pulsed exposures is:

$$L_{NIR} = \Sigma\, L_\lambda \cdot R(\lambda) \cdot \Delta\lambda \ \le\ 3.2/(\alpha \cdot t^{0.25})\ \ \mathrm{W/cm^2{\cdot}sr^{-1}} \qquad \text{for } t < 810\ \mathrm{s} \qquad [5]$$

$$\le\ 3.2/[(0.09\ \text{radian})(0.0008\ \mathrm{s})^{0.25}]\ \ \mathrm{W/cm^2{\cdot}sr^{-1}} \ =\ 19\ \mathrm{W/cm^2{\cdot}sr^{-1}} \quad \text{for } t < 0.8\ \mathrm{ms}$$

which is 29% of the limit L_{NIR}. This is a 3.5-fold safety factor. Greater safety factors actually exist since the conservative application of a smaller source size was used to determine radiance. With current technology, bare LEDs project a CW radiance less than L ~ 10 $\mathrm{W/(cm^2{\cdot}sr)}$; however, this is not biologically weighted. Staring (fixating) on a direct LED chip for any length of time is totally unrealistic. With normal viewing, eye movements blur the retinal image area for multiple-pulse exposure. This is one reason that the limits vary with exposure duration. An open question that may apply to chronic exposure over a lifetime is whether there exist any individuals who are particularly sensitive, such as individuals with impaired circulation, larger pupil sizes or on medication that might alter susceptibility to some biological effects.

3.2.4 Maximum Permissible Exposure Limits for Laser Radiation at 810 nm

Just for comparison, it may be informative to compare the exposure limits that apply to laser radiation, which have additional safety factors because of the nature of laser systems. This may also be useful because of the earlier attempts to include LEDs in the IEC laser product safety standard. The American National Standard Z136.1-2007 (ANSI, 2007), the laser guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2000) and the international Electrotechnical Commission (IEC) standard IEC60825-1.2007, all have the same Maximum Permissible Exposure (MPE) limit at 810 nm. The appropriate MPE is found in Table 5b, page 75 of ANSI Z136.1-2007. This is normally expressed as an irradiance E_{MPE}:

$$E_{MPE} = 1.8\, C_A \cdot C_E \cdot T_2^{-0.25}\ \text{mW} \cdot \text{cm}^{-2} \quad \text{for exposure durations exceeding } T_2 \qquad [7]$$

where C_A is a spectral correction factor [$C_A = 10^{0.002(\lambda\text{-700 nm})}$], which is 1.66 at 810 nm, C_E is a correction factor for extended sources which have an angular subtense α that is greater than α_{min} and less than α_{MAX} and is expressed as:

$$C_E = \alpha / \alpha_{min} \qquad [8]$$

where α_{min} = 1.5 mrad and α_{MAX} = 100 mrad = 0.1 radian and T_2 is:

$$T_2 = 10 \times 10^{(\alpha - 1.5)/98.5} = 100 \text{ s for } \alpha > \alpha_{MAX}, \text{ where } T_2^{-0.25} = 0.316 \qquad [9]$$

The maximum value of C_E occurs at α_{MAX} and is 66.7. Therefore, at $\alpha = \alpha_{MAX}$:

$$E_{MPE} = 1.8\,(1.66) \cdot (66.7) \cdot (0.316)\ \text{mW} \cdot \text{cm}^{-2} = 63\ \text{mW} \cdot \text{cm}^{-2} \qquad \text{for } t > T_2,$$

but this is only for $\alpha = 0.1$ rad, where the corresponding solid angle $\Omega = \pi \cdot \alpha^2/4 = 0.00785$ sr. Thus, if we divide the irradiance MPE by Ω, then the MPE can be expressed as radiance:

$$L_{MPE} = 8.0\ \text{W} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1} \qquad \text{for } t > 100 \text{ s}$$

Therefore, for all sources exceeding an angular subtense α > 100 mrad (~5.7°) the MPE can be expressed as a constant radiance of approximately 8 $\text{W} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1}$ and this is confirmed by referring to one standard that actually presents the limit for large sources in terms of radiance, i.e., in Figure 11 on page 78 of ANSI Z136.1-2007. Hence, no matter whether one stares at the source at close range, or wherever, if the time-averaged radiance of the source remains below this, the system would be safe for viewing. The time-averaged source radiance of an eyetracker system most typically will be much less. For an eyetracker that employs repetitive pulses, our example of a pulse width of 800-µs (t = 0.8-ms), the value of L_{MPE} would be increased by the ratio of $t^{-0.25} / T_2^{-0.25} = (5.95)/(0.316) = 18.8$ since all other correction factors in Equation [7] remain the same. Hence

$$L_{MPE} = 151\ \text{W} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1} \quad \text{for } t = 0.8 \text{ ms (single pulse)}$$

However, the single-pulse laser limit has a multiple-pulse correction factor C_P not applied in the incoherent exposure limits. For example, consider an LED source with a pulse repetition frequency (PRF) of 100 Hz. The correction factor $C_P = N^{-0.25}$ where N is the number of pulses in a train. Because of normal eye movements, the laser-safety guidance is to limit the pulse integration time to a 10-s maximum, as applied in accordance with the standard. For a 10-s exposure at a PRF of 100 Hz, N is 1000. And, $C_P = 1000^{-0.25} = 0.178$, which would reduce the pulse radiance MPE to $L_{MPE} = (0.178)(151) = 27\ W\cdot cm^{-2}\cdot sr^{-1}$ for a 100-Hz train of 0.8-ms pulses for a period of 10 seconds or greater. These laser limits are also not likely to be exceeded by an eyetracker LED emitter. It is important to recognize that the laser limits apply most directly to "point-source" viewing conditions as the default condition of exposure; hence, the added effort to convert the limits to radiance. ICNIRP clearly points out that the MPEs for incoherent sources should apply to all lamps such as LEDs, and not laser limits (ICNIRP, 1996, 1997, 2000; Sliney, 1997). Furthermore, the US Federal laser product performance standards do not apply to LEDs (CDRH, 1995). The above exercise was simply to demonstrate that even the more conservative laser exposure limits are not exceeded by most current infrared LEDs.

3.2.5 Retinal Irradiance Approach

If the apparent source-size subtends an angle α of the order of 100 milliradians or greater at a distance r = 100 to 200 mm, the radiance approach of measurement remains the best approach for assessing retinal hazards of an eyetracker. A 2-cm diameter source will produce an image diameter d_r at the retina of approximately 1.7 mm in diameter, since:

$$d_r = f\cdot\alpha \qquad [10]$$

where f is the effective focal length (in air) of the relaxed normal eye.

As noted in Appendix A, the radiance L measured at any distance from an extended source does not change. However, because typical infrared eyetrackers may have an array of LED sources, with overlapping irradiance patterns in the area of the face, the number of LEDs seen as bright sources and the appearance of the bright areas within each LED, will vary somewhat with viewing position. Also as explained in Appendix A, the retinal irradiance E_r is related to the source radiance L as:

$$E_r = 0.27\ L\cdot\tau\cdot d_e^2 \qquad [11]$$

where τ is the transmittance of the ocular media—which can be up to 0.9—and d_e is the pupil diameter in cm. This formulation (Sliney and Wolbarsht, 1980) assumes that E and L have units of $W\cdot cm^{-2}$ and $W\cdot cm^{2}\cdot sr^{-1}$, respectively. The exposures typical of LED eyetrackers are typically below Maximum Permissible Exposure (MPE) limits, and therefore well below actual retinal injury thresholds (Ham & Mueller, 1989; Sliney et al, 2005). The best available data for retinal injury thresholds for large-image exposure at 810 nm comes from work published by Ham and Mueller (1989); see Appendix C. The thresholds for visible retinal injury were several times larger than for exposures from an argon laser in the visible spectrum. The special conditions which apply to ophthalmic-instrument exposure (Borchert, Lambert & Sliney, 2006) require special consideration, but for the infrared eyetracker application, the individual is awake and task-oriented, viewing a display above or adjacent to the Infrared eyetracker source. The individual directs his or her gaze at specific instructions on the display, which would never have the individual fully dark-adapted. A computer monitor is considered sufficiently bright for normal working conditions at a luminance of $10 cd\cdot m^{-2}$ (see ISO 9241-3), which is relatively low indoor lighting, thus if one assumes some level of dark adaptation, the pupils could be larger than those typical of indoor illumination. Therefore, the underlying assumption of a dark-adapted (7-mm) pupil employed in the derivation of the retinal safety limit in Equation [7] provides a conservative limit. The question is whether the chronic exposure characteristic of gaze-directed communication is more extensive than was anticipated in the derivation of the ICNIRP limits.

4 Radiometric Measurements

4.1 Exposures

4.1.1 Exposures of the Eyes at Reference Points and for Normal Use.

Table 1 in Appendix A provides the measured values of irradiance at a reference distance of 20 cm. The actual intended use viewing distances will normally be greater (e.g., at about 50 cm). Measurements of total irradiance at the locations where the eyes would be exposed to one or more LEDs were made at lines of sight (l.o.s.) positions. Measurements were made with and without a calibrated 10% transmission filter to check for detector linearity and assure that the detector was not saturated; however, a comprehensive test for detector saturation and maximal detector alignment was not possible within the non-laboratory setting, which was the best available in the Brussels meeting. It must therefore be emphasized that the actual values in Appendix A could not be checked and may not always accurately reflect the emissions of each device tested.

4.1.2 Exposures of the Eye At the Closest Points of Access

To assure worst-case measurements or irradiance at close distances, and to ease alignment of the radiometer detector, any infrared window enclosure can be removed to maximize the measured emission levels. In a laboratory setting, where much more time would be available, the detector would be positioned for measurement of a part of an LED array, or an entire array for a multiple-LED source. Furthermore, with an array, a mask would typically be employed to block the emissions of all but one LED at 20 cm. This permits the measurement of the irradiance from a single LED at the distance recommended by IEC62471/CIE-S009 Photobiological Safety of Lamps and Lamp Systems, and ANSI/IESNA RP27.2-02.

4.1.3 Measurements of Ultraviolet Radiation (UVR)

There was no reason to expect that the LED illuminators would emit optical radiation outside of the IR-A spectral region, routine checks were made to detect the presence of UVR. To assure that there was no shorter-wavelength ultraviolet radiation emitted from the illuminators, measurements were made with the UV-Hazard detector head (i.e., S(λ)-weighted) and with the UV-A detector. No UVR was detected above the noise level of the instrument. The spectrally weighted UVR was less than 0.02 $\mu W/cm^2$-effective; the UV-A was less than 0.002 $\mu W/cm^2$.

4.2 Measurement of Source Characteristics

The eyetrackers that were measured at the COGAIN meeting in Brussels varied widely. Some had only a few LEDs, other had arrays, and still others had two widely separated arrays. Some LED packages actually consist of compact arrays of up to 60 surface-emitting gallium-aluminum-arsenide (GaAlAs) chips with a collimating lens to concentrate the infrared output as desired for the application. Using digital photography some of the LED arrays were imaged. However, to illustrate the technique, Figure 2 shows some representative images of a remote control rather than an eyetracker to illustrate the principle. The apparent source moves around within the window depending upon the position of the viewer. To provide a very conservative hazard analysis and to maximize the calculation of radiance, the effective emission area of only the central bright spot is routinely used for measurements and calculations. This permitted a calculation of the highest radiance. Furthermore, to assure worst-case calculations, the angular subtense α of the source for safety calculations can be based on the outside dome dimension at the 20-cm reference distance. In most of the eyetrackers, the emission was in a very diffuse ("Lambertian") pattern, or slightly tighter beam. Some beams could be more collimated if directed by the eyetracker. The estimation of the source size under the conditions of the demonstration in Brussels was quite limited.

		
Hand-held infrared LED controller seen on-axis	Hand-held infrared LED controller seen off-axis	Hand-held infrared LED controller with off-axis tilt

Figure 11. To illustrate the use of digital camera imaging to capture invisible infrared LED emitters, these images of a video remote controller were taken on-axis and slightly off-axis in two planes. Knowing the dimensions of the window, the actual source size can be quickly determined. A metric rule is sometimes placed adjacent to the source for more direct calibration.

4.3 CONCLUSIONS

The prototype Infrared eyetracker devices and the LED emitters employed in these systems tested in Brussels do not pose a potential hazard to the eye based upon current safety standards when used under realistic viewing conditions. Even when fixating on the LED for many minutes, the exposure would not exceed the applicable limits. LEDs are radiance limited and cannot produce exposure levels at the retina that even approach the levels that are known to cause retinal thermal injury (ICNIRP, 2000; Sliney, 1997) Currently, only short-wavelength blue-violet emitters clearly exceed the more restrictive photochemical hazard limits at wavelengths shorter than 550 nm. In other words, the infrared LEDs would have to emit far more power to pose a serious *acute* hazard to the retina. This is theoretically impossible for current LEDs.

Although the LED and lamp sources tested clearly pose no hazard to the eye for brief periods of viewing of some minutes—or even hours—when applied against current national and international ocular exposure limits for infrared optical radiation, there remains a question that should be addressed by an expert committee on whether the limits are truly adequately conservative for chronic daily exposure of the eye for decades. It is not clear whether any of the standards, which vary in their stringency, can be directly applied to the eye-tracking situation of gaze based communication.

There are no cognizable hazards to the cornea, lens or retina of the eye from even lengthy, repeated exposures to any bystander, such as a care-giver since the exposure distances would be characteristically greater and constant illumination is not realistic.

.

The following questions should be addressed by a CIE (International Commission on Illumination) technical committee (TC) to review the currently relevant standards and consider if the infrared exposure levels in current standards can be safely applied to the case of ongoing, day-long exposure. Furthermore, the TC should provide guidance on standardized techniques for measurement and hazard analysis for the range of eye-tracking systems and how to apply safety criteria.

In preliminary discussions within Division 6 of the CIE, the following terms of reference was discussed and potential committee membership from COGAIN participants and CIE Division 6 were considered. Other experts who have participated in Division 6 would be included. The draft terms of reference and membership of the committee are included in the appendices and have been discussed with the director of division 6.

David H. Sliney

David H. Sliney, Ph.D.

5 Medical issues and special populations

5.1 Special cases of communication through gaze interaction

People without disabilities might use a computer for work and leisure purposes. For many people with disabilities a computer offers the only means by which they can carry out work and leisure and is also the only means by which they can communicate socially. For example Keith, a person with ALS/ MND, who is unable to voluntarily move any part of his body. His eye control system is a) the only means by which he can do his job at work, b) the only way in which he can independently enjoy his leisure time, e.g. by surfing the web, emailing friends and playing games and c) an essential means by which he can communicate socially and independently since losing the ability to speak. To an extent he can achieve communication and control by means other than eye control. However, eye control offers him the only means by which he can achieve these things independently. Therefore, like many people with disabilities who are eager to use this technology for communication and control, Keith chooses to use the system for up to twelve hours per day. In addition to the length of exposure emitted by this infra red computer system, Keith also finds it impossible to blink or close his eyes, and as a result he is unable to lubricate his eyes in the same way as other people. In our experience, Keith's extensive use of his assistive technology is not untypical of many people with disabilities who are completely reliant on their system for all of their communication and control needs. Current infra red safety standards are of course designed for a range of devices to which the user is not usually exposed for a long period of time nor at such close proximity. For example, with a television remote control, the device will be used for a matter of mere seconds in each day and even then directed away from the eye to control the television as opposed to pointing directly at the eye in order to pick up eye movement.

5.1.1 Physical impairments leading to change in exposure situation

Today the users of eye control technology are often people with severe disabilities and degenerative conditions, for example ALS/ MND (Donegan et al. 2005). People with severe disabilities or degenerative conditions are more vulnerable to the risk of infection and injury. Not only this but infection or injury is more debilitating. Donegan et al (2005) identified a range of user groups who benefit from eye control technology. Except for people with repetitive strain injury, these groups include people with neurological conditions. Some of the physical impairments experienced by people with neurological conditions leading to a change in the exposure situation include reduced mobility, sensation, nutritional status, fatigue, visual impairment and cognitive ability. Reduced mobility restricts the ability of someone to independently change their own position or that of their computer. Consequently, they have difficulty moving away from the source of infra red light independently. Unlike people who are mobile and who frequently change their position. Instead, they rely on having the ability to pause or switch off the equipment.

Eyelids protect the eyes through removing debris and spreading moisture (tears). Tears are rich in both antibodies and nutrients and spread oxygen to the cornea. However, when the eyelids are not functioning normally the cornea is at risk of becoming infected, dried or injured. (www.merck.com). This poses more risk for someone who is dehydrated or under nourished. Abnormal eye sensation such as pain can intensify through increased exposure to light (www.merck.com). Fatigue is associated with certain neurological conditions. The result of which is that tasks take longer, thus more time is spent at the computer. However, because eye control technology is so effective as an access and communication tool, people with severe disabilities and degenerative conditions who do not have any other means of computer control may hold a different view to that of a non disabled person about the benefits of pacing and taking regular breaks.

Finally, some people are simply more sensitive to light than others and as we grow older our sensitivity to light increases (www.rnib.org.uk)

5.1.2 Medications which effect light sensitivity

Initial searches suggest there are a wide range of medications which heighten light sensitivity. Only a small number of examples are given here; E.g. tetracycline (a common antibiotic), to digitalis (used to treat heart failure) to tropicamide or cyclopentolate (found in eye drops to dilate the pupil), and even Plaquenil which is prescribed for rheumatoid arthritis. Some medications affect the eyes in other ways. For example, 'dry eyes' is a side effect of certain common, non steroidal anti-inflammatory drugs. (www.causeof.org/sensitivity; www.merck.com). However, a medical opinion is required in order to determine how significant the effects of the medication are upon sensitivity to light, especially when taken in specific doses and over certain periods of time.

5.2 Conclusion

Regarding infra red safety standards, Dr Sliney has advised in the report included in this document that "the limits vary with exposure duration. An open question that may apply to chronic exposure over a lifetime is whether there exist any individuals who are particularly sensitive, such as individuals with impaired circulation, larger pupil sizes or on medication that might alter susceptibility to some biological effects". Individuals who use eye control technology do so in all likelihood for many hours per day, have a severe physical disability or degenerative condition, and take medication.

6 Next steps

6.1 Future Work – Next Steps

This section outlines the aims and objectives of the proposed technical committee, the procedures involved in developing a standard. Information regarding the structures within the CIE are taken from the CIE code of procedure for divisions and technical committees, 1999, with supplement 2001, Central Bureau of the CIE. The following outlines the membership of the proposed TC, and there follows a short outline of the outcomes proposed as part of this Technical Committees' work which will be most beneficial for COGAIN user communities and researchers.

6.1.1 The CIE - who they are and what they do

The CIE (Commission internationale de l'éclairage) is the international authority on light, illumination, colour and colour spaces. It is an independent, non-profit organisation which serves member countries on a voluntary basis. It was founded in 1913 and is recognised by ISO and other safety authorities. The CIE has agreements with the International Standardisation Organisation (ISO), the International Electrotechnical Commission (IEC), the European Committee for Standardisation (CEN) and the International Committee for Weights and Measures (CIPM).

The CIE has seven divisions, which establish Technical Committees in order to carry out standardisation. The division relevant to our work is Division 6; Photobiology and Photochemistry. This division studies and evaluates the effects of optical radiation on biological and photochemical systems, and is directed by Dr. Ann Webb. Each division proposes a working programme including proposals for Technical Committees (TC) to the Board of Administration, for approval. The code of practise also involves furthering the objectives of the CIE where possible and relevant by conducting or participating in discussion (seminars, symposia or conferences), liasing with other international organisations and promoting the publication of material on CIE activities outside the CIE.

6.1.2 The structure of a Technical Committee

When a division wishes to establish a TC, it proposes a terms of reference including type of publication, a working programme including timetable, and a Chair of the committee. The functions of the Committee Chairperson are to coordinate the work of the TC, ensuring that all knowledge and viewpoints are considered, and that the TC keeps to its terms of reference and time schedule, conducting TC meetings and keeping records and minutes, preparing drafts of publications, and reporting to the Division.

Members of Technical Committees are appointed by the Chair on approval of the Board, and need not be members of the Division. They must be experts on the items referred to in the working programme and must represent the range of knowledge and viewpoints which exist. Meetings should be held as often as necessary and practicable, in order to complete the task within the allocated time. On completion of the specific task, usually publication, the TC is dissolved and all background material is sent to the Central Bureau of the CIE for archiving.

CIE standards will usually be concise documentation of data and procedures defining aspects of light and lighting for which international harmony requires such unique definition. On the basis of agreements between CIE, ISO and IEC it is to be expected that CIE standards will be taken, essentially unaltered, into universal standard systems. Standards shall reflect majority opinion, however all efforts should be taken to reach consensus.

6.1.3 Proposed Technical Committee

COMMISSION INTERNATIONALE DE I'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION
Central Bureau: Kegelgasse 27 - A-1030 Wien - AUSTRIA

DIVISION 6 Photobiology and Photochemistry

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14th January, 2008

PROPOSED CIE DIVISION 6 TC

Technical Committee TC 6-64(?) “Optical Safety of Infrared Eyetrackers Applied for Extended-Durations”

TERMS OF REFERENCE: To review the potential optical radiation hazards from infrared eye-tracking systems when exposure durations are continuous throughout the day. Emphasis is placed upon the use of eye-tracking for gaze-based communication for severely disabled persons, which requires exposure of the eyes throughout a day over many years. Although there exist exposure guidelines from the International Commission on Non-Ionizing Radiation (ICNIRP) for infrared exposure and a CIE Standard (S-009) for photobiological safety of lamps and lamp systems, the lengths of exposure employed in this type of interface technology for disabled users may exceed the durations envisioned in the current exposure guidelines and standards. Abnormalities in the eye behaviour of severely disabled users may also require special treatment in safety standards.

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MEMBERSHIP:

Dr. Jean-Pierre Cesarini (France)	[Photodermatology]
M. Jacques Charlier (France)	[Electro-optics technology]
Mr. Dixon Cleveland (USA)	[Electro-optics technology]
Assoc. Prof. Dr. Gintautas Daunys (Lithuania)	[Electronics, Physics]
Mr. Detlev Droege (Germany)	[Electro-optics technology]
Dr. Michael Donnegan (UK)	[Disability & Assistive Technology]
Mr. Markus Joos (Germany)	[Electro-optics systems technology]
Ms. Fiona Mulvey (Germany) - Secretary	[Cognitive science, vision science]
Dr. David H. Sliney (USA) - Chair	[Biophysics, optical radiation safety]
Dr. Karl Schulmeister (Austria)	[Biophysics, laser safety]
Mr. Mårten Skogö (Sweden)	[Electro-optical systems technology]
Dr. Per Söderberg (Sweden)	[Ophthalmology]
Prof. Olga Štěpánková (Czech Republic)	[Electrical Engineering/Cybernetics]
Dr. Arantxa Villanueva (Spain)	[Electrical/Electronic Engineering]

[***Note***: In some cases it is necessary to have more than one member from a single country because of quite different expertise.]

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6.2 Future Work - Communicating the results and information dissemination

An important part of COGAIN objectives is to disseminate the results of research to users and members of industry. With this in mind, we propose a number of documents which aim to provide a clear an objective statement of the findings, and outline best practises to both users and designers for safe eyetracking. These documents will be made publicly available through the COGAIN website.

6.1.4 Proposed documents for communicating findings

Firstly, based on the expertise available within the CIE and our own consortium, we aim to provide practical advise to users and carers on best practices when using an eyetracker. This could include simple measures such as using eye drops to prevent dry eyes, or taking a break when using the system, as well as more detailed information for particular medical conditions.

Secondly, we aim to produce a list of best practices for designers of eyetracking systems as a support mechanism in complying to safety standards and a clear outline of what is necessary and desirable in a safe system. This could include such simple measures as providing a means of switching on and off the IR sources without shutting the system down, as well as clear information on the calculation of permissible output and the practical implementation of the resulting standard. These documents will represent the best available knowledge and will be publicly available on the COGAIN website.

6.1.5 Proposed COGAIN and CIE safety approval for commercial and prototype systems

One desirable result of collaboration between COGAIN and the CIE would be to be able to provide safety approval for commercial systems, on request. COGAIN and CIE approval may be considered for systems which demonstrably comply to safety standards.

Appendix A: Measurements

Device	Real D_L[mm] [eff D_L] etc	E-avg at 20 cm [µW/cm^2]	D_L [mm]	Cycle time [ms]	Pulse width [ms]	Radiance L	PRF /duty cycle	distance	L_{peak}	Wavelength λ	No LED	IR Retinal MPE
System 1		650	3	1	3	3.6689	3	20	1.223			40
System 2	2.5 mm [5 mm effective]	250	5			0.5080		20				24
System 2	2.5 mm [4.3 mm effective]	411	4.3			1.1292		20				27.9
System 4	CW	88	2.5			0.7153		20				48
System 5	70 mm instead of 200 mm dist	185	2.5	1.25	0.125	1.5037	0.1	7	15.04		4	16.8
System 6	CW	275	3.5			1.1404		20			1	34.3
System 7	CW and 6 mm [16.8 effective]	5100	16.971			0.8996		20			8	7.07
System 8	CW	966	6			1.3631		20			1	20
System 9	3.mm [15 mm for 25 seen est.]	650	15	70	5	0.1468	0.07142857	20	2.055		45	8
System 10	apparent LED tracking	270	3.5	16	3	1.1197	0.1875	20	5.972			34.3
System 11	Max of lower two 60-LED arrays	550	14	25	4	0.1426	0.16	20	0.891			8.57

Table 1. Representative Measurements Obtained at the COGAIN Measurement workshop, Brussels, 22 Nov 2007#

Notes: Radiance L and IR Retinal MPE are in units of $W \cdot cm^{-2}\text{-}sr^{-1}$; CW = Continuous-Wave (not pulsed); IR Lens MPE = 10 $mW \cdot cm^{-2}$

Because of the time available and insufficient time to test for detector saturation in pulsed modes, etc., and to perform careful measurement of the source sizes, the above measurements and calculated values should only be indicative, as the objective of the Workshop was to demonstrate measurement methods that might be used in a laboratory setting.

Appendix B:
Explanation of Technical Terminology

This Appendix provides relevant knowledge of radiometry for readers not familiar with the topic.

Solid angle Ω

The solid angle itself is not a radiometric quantity, but rather a unitless ratio defined in three dimensions comparable to the radian in two dimensions. In other words, the solid angle is to the surface of a sphere what a normal angle segmenting a circle is to the circumference of that circle The solid angle is part of the radiometric quantities *radiant intensity* and *radiance*.

Definition:

The solid angle describes the geometrical distribution of a volume which extends (expands) linearly from one point of origin. It is calculated as a product of 4π and the ratio of the area of intersection between this volume and an imaginary sphere with the same point of origin ΔA_K to the total area of the same sphere A_K (s. Figure 1).

It is noteworthy that the shape of the area of intersection ΔA_K is arbitrary, for example circular or rectangular.

Depending on the physical properties to be described with the solid angle, one assigns one or more certain properties to this volume which makes it different to the ambient space.

For the purposes of describing the spatial distribution of radiation from a certain source, one assigns to the volume the property of limiting the radiation containing space.

$$\Omega = 4\pi \times \frac{\Delta A_K}{A_K} \qquad [1] \qquad \text{or with } A_K = 4\pi r^2 \qquad \Omega = \frac{\Delta A_K}{r^2} \qquad [2]$$

Unit:

For practical purposes, the auxiliary SI unit sr (steradian) is assigned to the (actually unitless) solid angle Ω.

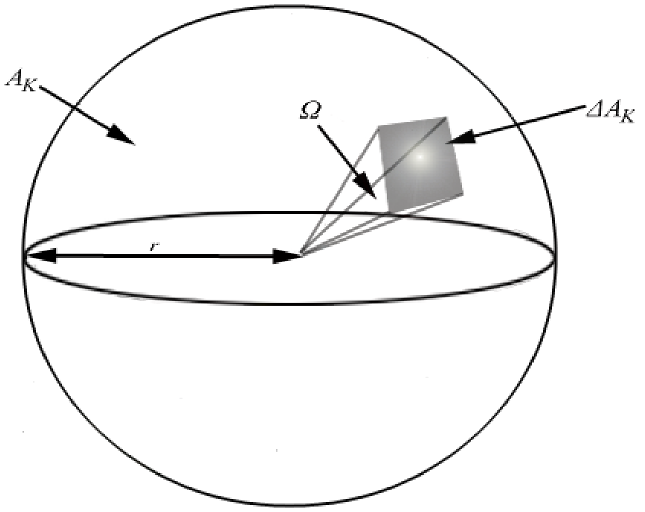

Figure 12: Illustration of the solid angle

For a common type of solid angle, the *canonical* one, the following *transformation* to the angle φ can be employed (s. Figure 2):

The size of the spherical cap ΔA_K is:

$\Delta A_K = 2\pi rh$ [3] From this it follows that: $\Delta A_K = 2\pi r^2(1-\cos\varphi)$ [4]

Insertion of [3] into [4] leads to:

$$\Omega = 2\pi \times (1-\cos\varphi) \quad [5]$$

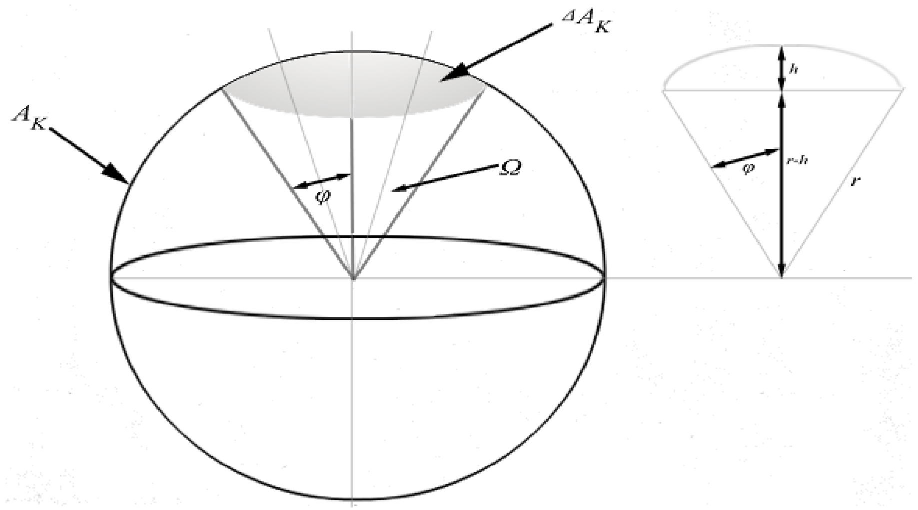

Figure 13: Illustration of transformation of the canonical solid angle Ω to the angle φ

Radiant energy Q

Definition:

Radiant energy corresponds to the energy that is emitted by an object in all directions or received by an object from all directions.

Unit:

The SI unit of radiant energy Q is the J (oule).

Radiant power Φ

Definition:

The radiant power (also called radiant flux) is the quantity of energy ∂Q emitted by an object per unit of time ∂t in all directions or received by an object per unit of time from all directions.

$$\Phi = \frac{\partial Q}{\partial t}$$

Unit:

The SI unit of radiant power Φ is the W (att).

Radiant intensity I

Definition:

Radiant intensity is defined as radiant power $\partial\Phi$ per unit solid angle $\partial\Omega$ of a *point source*.
If the intensity is the same in all directions, the source is called isotropic. Whenever a source does not have the same power in all directions it is said to be anisotropic.

$$I = \frac{\partial\Phi}{\partial\Omega}$$

Unit:

The SI unit of radiant intensity I is $\frac{W}{sr}$.

Radiance L

Definition:

Radiance is defined as radiant power $\partial\Phi$ per unit solid angle $\partial\Omega$ and per unit *projected* source area $\partial A\cos\theta$ of an *extended source*. Thereby θ is the *projection angle* between the surface normal and the specified direction (s. Figure 3).

$$L = \frac{\partial^2\Phi}{\partial\Omega\partial A\cos\theta}$$

Unit:

The SI unit of radiance L is $\frac{W}{m^2 sr}$.

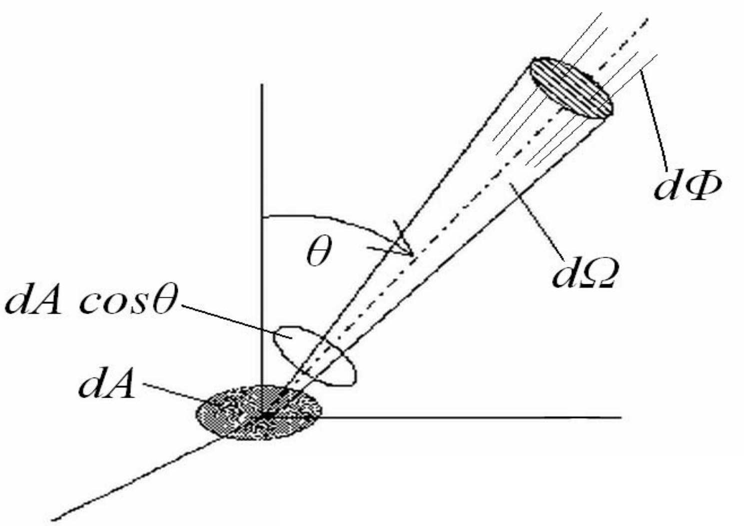

Figure 14. Radiance of an extended source

Radiance is an important measure in eye safety standards. The reason for it's suitability as quantity for exposure limits is due to the fact that it can be used to calculate how much of the radiant energy emitted by an extended source can be concentrated by an optical system (i.e. lenses or reflectors) which is directed towards this source under the projection angle θ. In the case of the eye directed at a light source, the solid angle of interest is the area of the pupil.

Conservation of Radiance

A given radiance can not be increased by an optical system, although *irradiance* is increased when the optical system focuses an image onto a smaller plane. Radiance, however, is a constant, and provided that no light is absorbed by the lens, radiance will be at least the same (and possibly greater) at the light source as it is when the image is passed through the lens and focused on the retina.

Irradiance E

Definition:

This is the radiant power $\partial\Phi$ on a surface per surface unit ∂A from all directions of a hemisphere.

$$E = \frac{\partial\Phi}{\partial A} = \int_{\Omega} L \cos\varphi \partial\Omega = \frac{\partial I}{\partial d^2}$$

Unit:

The SI unit of irradiance E is $\frac{W}{m^2}$ or, otherwise expressed, W·cm$^{-2.}$

Inverse Square Law

The irradiance produced on a surface by a point source is inversely proportional to the square of the distance (s. Figure 4).

$$E_{A1} = (d_2 / d_1)^2 E_{A2}$$

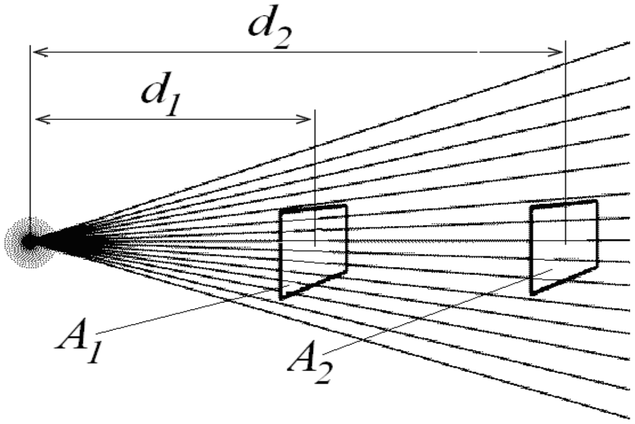

Figure 15. Inverse Square Law

Spectral quantities

All of the previous definitions can be applied to a narrow wavelength range centred around λ. They can be noted by adding a λ subscript such as: $Q_\lambda, \Phi_\lambda, I_\lambda, L_\lambda,\ E_\lambda$

The unit for each spectral quantity is modified by adding nm^{-1}, e.g. $\frac{W}{m^2}$ becomes $\frac{W}{m^2 nm}$.

Point source vs. extended Source

The radiometric quantities above are defined in relation to two different kind of sources, the point source and the extended source. Unlike the latter, the point source (since a point has no area) exists only as a useful theoretical construct.

If the extension of an extended source is one tenth or less than the distance to the target object, one can regard it as a point source. In terms of the eye, the definitions above which are restricted to point sources can be used for real sources if the distance between the source and the eye is at least ten times the size of the source.

Appendix C:
Calculations used in existing Standards

RETINAL IRRADIANCE AND RETINAL INJURY

C.1 Retinal Irradiance and Source Radiance

Guidelines preventing retinal injury from human exposure to intense light sources are expressed in terms of radiance. There are several advantages: the radiance L is directly related to the retinal irradiance E_r is directly proportional to the source radiance L, and the radiance measured at any distance does not change, i.e., radiance does not change with viewing distance—unless the source of energy becomes sufficiently distant that it is not resolved. The relation is:

$$E_r = 0.27\, L \cdot \tau \cdot d_e^2 \qquad [A1]$$

where τ is the transmittance of the ocular media—which can be up to 0.9—and d_e is the pupil diameter in cm. This formulation (Sliney and Wolbarsht, *Safety with Lasers and Other Optical Sources,* New York, Plenum Publishing Corp., 1980) assumes that E and L have units of $W \cdot cm^{-2}$ and $W \cdot cm^2 \cdot sr^{-1}$, respectively.

C.2 Retinal Injury Thresholds at 810 nm

The best available data for retinal injury thresholds—stated at the retina—for large-image exposure near 810 nm comes from work published by Ham and Mueller (1989). They used a filtered xenon-arc lamp at 820 nm and found thresholds of approximately 25 W/cm^2 at 1 s; ~ 15 W/cm^2 at 10 s: and approximately 12 W/cm^2 at 100 s for 500 μm diameter circular images. All studies of retinal thermal injury show that the threshold for injury at 810 nm would be essentially the same as the threshold at 820 nm.

The retinal image size for small images is proportional to the effective focal length of the human eye in air, which is 17 mm:

$$d_r = \alpha \cdot f$$

d_r = (0.05)(17 mm) = 0.85 mm = 850 μm at the closest standard lamp viewing distance of 20 cm.

Using the relationship of retinal irradiance E_r to source radiance in [A1] becomes:

$$L = 3.7\, E_r / \tau \cdot d_e^2 \qquad [A2]$$

and the retinal irradiance threshold of 12 W/cm^2 for a 100-s exposure in a 500-μm retinal image corresponds to a source radiance L of:

$L = 3.7\, E_r / \tau \cdot d_e^2 = 101\ W/cm^2 \cdot sr^{-1}$ for a 7-mm diameter pupil, where the pupillary diameter d_e is expressed in cm.

However, for a more realistic pupil size for a well-lit indoor environment of 3 mm, the radiance for this 500-µm, 100-s threshold would have to be approximately:

$L = 548\ \mathrm{W/cm^2 \cdot sr^{-1}}$ for a 3- mm pupil

These radiance values would apply to a 500 µm image size, and the retinal irradiance thresholds decrease nearly inversely proportional to the image size up to nearly 1,700 µm. Thus for image sizes of the order of 1000 µm, the thresholds would be reduced by a factor of two-fold, and for the limiting case of 1,700 µm (where $\alpha = 100$ mrad in the human eye), the above thresholds would be extrapolated by dividing them by $(1700/500) = 3.4$. Hence the threshold radiances would be:

$L = 29.6\ \mathrm{W/cm^2 \cdot sr^{-1}}$ for a 7- mm pupil and for 100-s, 1,700-µm threshold

$L = 161\ \mathrm{W/cm^2 \cdot sr^{-1}}$ for a 3- mm pupil and for 100-s, 1,700-µm threshold

The ELs (TLVs) were derived for a 7-mm pupil, so the apparent safety factor in the MPEs for large retinal image sizes is near four-fold (3.7-fold for this example).

Appendix D: Correspondence with the CIE

Letter to standardising bodies

To whom it may concern,

I am writing on behalf of the COGAIN (Communications through Gaze Interaction) network of excellence which is funded under the EU projects initiative to develop and promote the use of eye tracking enabled technology for persons with physical disability. This Network consists of a consortium of research institutes across Europe, a Board of User Communities and a Board of Industrial Advisors. The users in our group are generally totally dependent on such technologies in order to communicate, due to loss of voluntary movement and speech.

We have received a directive from our Board of User Communities to investigate the safety of using eyetrackers on a long term, daily basis. Eye tracking technology has begun to be applied to user situations outside academic research, and typically involves exposure to directed near Infra Red light in order to illuminate the eye. Our users would typically be exposed to this light up to and above 8 hours a day. The eyetracker manufacturers we have contacted quote various standards they use in order to assure the safety of their systems, however, with the exception of one standard from the U.S. Department of Health, Education and Welfare[6] (later an ANSI standard), there seems to be no standard which take into account such long exposure times, or are particularly directed at eyetracking technology. Research suggests that the relationship between exposure time and potential damage to the eye (i.e. thermal injury, damage to the lens and / or retina) is not linear, and that different formulae should be used in assessing the Maximal Permissible Exposure levels for these longer exposure periods. Therefore we would greatly appreciate if you could lend the expertise of your consortium to this problem and advise us on our task.

Our consortium is applying our combined expertise in order to deal satisfactorily with this issue with a view to providing our users with an independent assessment of the safety of using these systems. Therefore, as a first step in reaching our aim we would like to ask your opinion on these matters, namely;

1. Do you consider that any of the existing standards for Infra Red exposure levels, which typically quote maximum exposure times of 1000seconds in their calculations, can be safely applied to the case of ongoing, day-long exposure?
2. Can you provide our consortium with any practical assistance should we attempt to measure the IR output of various eyetracking systems and apply safety criteria?
3. Would you be in a position to provide us with collaborate with us in developing standards which apply directly to this technology, as it increasingly sold in the open market as a communication aid, usability measure for web design/graphic displays and enters the gaming industry?

We would very much appreciate your considered response to these questions, and would like to offer the expertise of our consortium should you wish to access such equipment or consult with us.

Yours Sincerely,

Fiona Mulvey & Arantxa Villanueva

On behalf of COGAIN

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16th July, 2007

Dear Drs Mulvey and Villanueva,

Thank you for your letter to CIE Division 6 on behalf of COGAIN. This is the sort of issue that comes under the remit of Division 6, but I regret to say that we have no answers for you at this time.

The CIE has recently held its Quadrennial Symposium, including Division meetings, and I had the opportunity to discuss your letter with our resident "eye expert" Dr David Sliney. However, I understand that you have already approached him personally, so I leave him to give his reponse directly to you, rather than through me.

You are correct that there is no standard that considers the sort of eye tracking device and lengths of exposure that you are aiming to employ. Whether this is an issue or not I do not know, but let me explain to you how the CIE mechanism works in developing standards, then you can consider if we could work on this together.

The work of CIE takes place in Technical Committees, which culminate in a TC report or Standard (usually the former, followed after approval through use by the latter, but a Standard is also sometimes the initial output of a TC). Each TC must have a Chair, Terms of Reference, and for a Standard at least 5 members from different countries. If approved by the Division and CIE Board the TC begins its work, and should aim to produce its report within 4 years (though this is not always strictly adhered to, especially if there is still experimental work to complete). I regret to say that there is no funding for any of this: all work is voluntary and people give freely of their expertise and laboratory time. If you have the experimental capability to contribute and are looking for (eye) standards expertise to enable an informed decision on the need (or not) for a standard in this area then maybe we should explore the establishment of a TC.

I leave you to consider this when you have gathered responses from other interested parties. If you require any more information then please do not hesitate to contact me.

Sincerely yours,

Ann R. Webb
Director, Division 6.

Appendix E: References and Bibliography

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