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Technical Note

Analysis of Intensity Limits for Light Emitting Diodes Used in Toys and Consequences for Children's Visual Health

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Abstract: The analysis of the current safety standards for electric toys showed that the normative intensity limits for visible light emitted by LEDs integrated in toys are overestimated. These limits were originally set in a scientific article published in 2012 that was adapted into the international safety standard published in 2017, and into the subsequent European and national standards, all published in 2020. The overestimation of the intensity limits results from several errors made in the original article. Accordingly, the current normative intensity limits for visible light used in toys do not protect the children's eyes against adverse effects of exposure to high intensity LEDs which may compromise their visual health. Updating the safety standards for electric toys using a method based on robust scientific data is recommended to protect children's visual health and ensure their long-term well-being.

Keywords: LED; toys; optical safety; photobiology; retina; glare; macular injury; blue light hazard

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Introduction

Light-emitting diodes (LEDs) are energy-efficient light sources with a wide range of intensities and spectral distributions. Their versatility, ease of operation, and low cost have made them widely used in toys in which they fulfill various functions, such as simple indicators or sophisticated color-changing pattern projectors.

Ensuring the safety of toys equipped with LEDs is crucial as light transmittance is higher in children's eyes, increasing the risk of phototoxicity compared to adults. [1] Given the small size of LEDs, even a modest radiant flux can result in very high radiance and luminance values. [2] The potential risks of light exposure for the eyes are described in the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines. [3] In the visible range, an acute exposure to visible light in the blue part of the spectrum may cause retinal photochemical damage, which may irreversibly alter vision.

The latest international safety standard for electric toys was published in 2017. [4] It defines luminous and radiant intensity limits to ensure the optical safety of the LEDs incorporated in toys.

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This standard was adopted in 2020 as a European standard, [5] then transposed to national standards in 34 countries.

The intensity limits defined by the currently approved standards are based on an assessment method described in a scientific article published by Higlett and colleagues in 2012. [6] The limits were established for LEDs emitting in the visible and in the ultraviolet spectral ranges. While radiant intensity limits in the ultraviolet range were correctly derived in this paper, the determination of intensity limits in the visible spectrum, which concerns most of the LEDs used in toys, was, in our opinion, erroneous.

Because of these errors, which are detailed below, the luminous and radiant intensity limits for visible light emitted by LEDs in toys are largely overestimated in the safety standards. These limits fail to protect the eyes of children against retinal hazards and the consequences of repeated exposures to the intense glare caused by high intensity LEDs.

Analysis of the Intensity Limits for LEDs Used in Toys

Higlett and colleagues described an assessment method for determining the optical radiation safety of light-emitting diodes (LEDs) used in toys. [6] They determined accessible emission limits in terms of radiant or luminous intensity. These specifications are usually provided in the technical datasheet of the LEDs. Therefore, the toy manufacturer can select compliant LEDs without performing specific optical safety tests.

The analysis of the article of Higlett and colleagues revealed errors in the sections concerning the determination of limits for visible light. The three errors are the following:

- Incorrect assessment of the foreseeable misuse exposure scenario
- Incorrect derivation of luminous intensity from luminance
- Numerical errors in the computation of radiant intensity limits

Firstly, Higlett and colleagues incorrectly assessed the retinal photochemical hazard in the foreseeable misuse exposure scenario (exposure at a distance of 100 mm during 100 s). They did not consider the spatial averaging process across the effective acceptance angle recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [3] to account for involuntary eye movements. As a result, Higlett and colleagues concluded that this scenario was not restrictive in comparison with the worst-case condition of normal use at 200 mm during 10 000 s. They rejected the foreseeable misuse scenario. Due to this error, the safety limits concerning the retinal effects of short wavelength optical radiation (blue and violet light) were overestimated by a factor of 4.

Secondly, Higlett and colleagues incorrectly calculated luminous intensity from a luminance value of 10 000 $cd{\cdot}m^{-2}$, a threshold defined as a simple guideline by the ICNIRP to avoid complex measurements of white light sources. [3] Their calculation ignored the apparent size of the LED, leading to largely overestimate the luminous intensity limits, expressed in unit of cd. The error factor is about 1 000. The consequence of this error is that LEDs used in toys can be extremely bright, with luminance values that may exceed 10^7 $cd{\cdot}m^{-2}$.

Thirdly, a numerical error was identified in the computation of the radiant intensity limits by Higlett and colleagues, resulting in values 10 times higher than the true radiant intensity limits, already overestimated due to the error reported above. Consequently, when referring to emission limits expressed in unit of $W{\cdot}sr^{-1}$, LEDs can have luminance values which may be around 10^8 $cd{\cdot}m^{-2}$.

Greater detail concerning the three errors can be found in the Appendix A.

Implications for Children's Visual Health

While using electric toys complying with the current safety standards, children may be exposed to high intensity LEDs at short distances, causing repeated temporary losses of vision (saturation glare) and afterimages persisting in the visual field because of the photobleaching of the retinal photoreceptors. [7] Furthermore, the exposure dose may exceed the limit for photochemical retinal damage by a factor of 4, increasing the risk of acute effects such as photoretinitis. [3]

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Damage to the retina is potentially cumulative, leading to eye pathologies during adulthood suspected to be linked with repeated exposures to bright sources and intense glare, such as age-related macular degeneration (AMD) [8] or glaucoma. [9]

The risks presented by high intensity LEDs can only be mitigated by the aversion response of children. However, the aversion reaction may not be fully developed in young children whose retina is immature. Furthermore, the eyes of infants younger than two years of age have a shorter focal length, [10] which implies that they are likely to manipulate their toys at short distances, typically less than the distance of 200 mm that was chosen by Higlett and colleagues to define the intensity limits of LEDs.

With older children, the aversion response can be intentionally ignored for playing purposes as described in recent case reports of macular injuries in children exposed to a hand-held high intensity LED device [11] or to a laser pointer [12] during games. Besides, LEDs emitting pure blue light are not perceived as being very bright due to the lower sensitivity of vision in this spectral range, even when radiant intensity is high. [13] In this case, without high brightness cue, the aversion response is very limited, or non-existent. [1,14]

Safety Standards

The errors found in the article of Higlett and colleagues [6] were integrally transposed into the international safety standard for electric toys, into the equivalent European standard, and into 34 national standards. The overestimation of the safe intensity limits for visible light emitted by LEDs prevents the current standards from providing adequate protection against the harmful effects of high intensity LEDs incorporated in toys.

Conclusion

It is recommended to revise the normative intensity limits of LEDs used in toys to correct the existing errors and ensure adequate protection of children's visual health. Regulatory agencies and health authorities should take action to update these standards.

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Appendix A. Explanations of the Errors Identified in the Original Article of Higlett and Colleagues: Higlett MP, O'Hagan JB, Khazova M. Safety of Light Emitting Diodes in Toys. *J Radiol Prot* 2012; 32: 51–72.

<u>Error 1: incorrect assessment of the foreseeable misuse scenario</u>

Two exposure scenarios were used by the authors to define the accessible emission limits (AELs) for visible light (page 54 of the original paper):

- Scenario 1 corresponding to a worst-case condition of normal use at 200 mm from the eyes for 10 000 s,
- Scenario 2 corresponding to a foreseeable misuse scenario at a viewing distance of 100 mm for 100 s.

In the first scenario (page 55), Higlett and colleagues used the blue light hazard exposure limit of 100 $W \cdot m^{-2} \cdot sr^{-1}$ (B-lambda weighted radiance) defined by the International Commission for Non-Ionizing Radiation Protection (ICNIRP) in their guidelines. They used the ICNIRP effective size of source of 0·11 rad (acceptance angle corresponding to a solid angle of 0·01 sr), leading to an exposure limit of 1 $W \cdot m^{-2}$ (B-lambda weighted irradiance) at the eye and a corresponding AEL of (0·04 × Ω) W in terms of B-lambda weighted flux emitted by the LED, where Ω is the solid angle of the LED beam.

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Surprisingly, Higlett and colleagues used a different method for evaluating the AEL in the second scenario (page 55). They correctly used the ICNIRP exposure limit of 10 000 $W \cdot m^{-2} \cdot sr^{-1}$ (B-lambda weighted radiance) corresponding to an exposure of 100 s, but they multiplied it by the solid angle Ω of the LED beam and by the square of the viewing distance, thereby ignoring the ICNIRP acceptance angle. Their calculation gave an AEL of (100 × Ω) W, a value which is 2 500 times higher than the AEL of Scenario 1. They thus rejected Scenario 2 as they judged that it was not restrictive for optical safety, in comparison with Scenario 1.

Should Higlett and colleagues have used the ICNIRP acceptance angle as they did for the first scenario (for an exposure of 100 s, it is 0·011 rad, which is equivalent to a solid angle of 0·0001 sr), they would have found an AEL of (0·01 × Ω) W. Scenario 2 is actually 4 times more restrictive than Scenario 1. Scenario 2 should have been the one to consider in the assessment of optical safety.

Error 2: incorrect consideration of the ICNIRP luminance threshold of 10 000 cdm^{-2}

The luminance threshold value of 10 000 $cd \cdot m^{-2}$ was considered by Higlett and colleagues on page 56 of the original paper to establish safe limits for visible optical radiation, following the ICNIRP guidelines stating that below this indicative value, retinal exposure limits for the blue light hazard and thermal injury would not be exceeded in the case of light sources with a broad spectrum. [3]

Higlett and colleagues calculated the luminous intensity value corresponding to a luminance of 10 000 $cd \cdot m^{-2}$ using Equation 3 on page 56 of the article. This equation contains a parameter named *Area*. Higlett and colleagues defined this parameter as being the area of the beam at the eye. This is incorrect because luminous intensity is the product of the luminance and the apparent source area, which is usually much smaller than the area of the beam at the eye. For instance, if an LED of 10 000 $cd \cdot m^{-2}$ has an apparent area of 4 mm^2, its luminous intensity is 0·04 cd.

In the paper, the luminous intensity values corresponding to a luminance of 10 000 $cd \cdot m^{-2}$ can reach 38·4 cd, as shown in Figure 7 (page 58 of the original article). Unfortunately, this luminous intensity value corresponds to LEDs having a very high luminance that may reach more than 1 000 times the ICNIRP guideline of 10 000 $cd \cdot m^{-2}$. For example, an LED of 38·4 cd with a typical apparent area of 4 mm^2 has a luminance of about 10 000 000 $cd \cdot m^{-2}$, far beyond the 10 000 $cd \cdot m^{-2}$ threshold considered by Higlett and colleagues to limit the luminance of LEDs.

Error 3: incorrect determination of emission limits expressed in unit of radiant intensity

A threshold of 0·76 $W \cdot sr^{-1}$ was used by Higlett and colleagues to provide a limit to the AEL curves expressed in unit of radiant intensity, as shown in Figure 9 (page 59 of the article). This value corresponds to luminous intensities that may largely exceed the limit of 38·4 cd, which was already overestimated due to Error 2. Based on our own calculations, we can conclude that Higlett and colleagues made an error of a factor of 10 in establishing the radiant intensity threshold.

To illustrate this error, we can consider a white LED having a radiant intensity of 0·76 $W \cdot sr^{-1}$ and a correlated colour temperature of 5 410 K. The corresponding luminous intensity is 250 cd, a value that exceeds the limit of 38·4 cd previously derived by the Higlett and colleagues. The combination of Error 2 and Error 3 would lead to wrongly considering that this white LED is safe for the eyes. If this white LED has an apparent area of 4 mm^2, its true luminance is 62 500 000 $cd \cdot m^{-2}$. Again, this value is far beyond the 10 000 $cd \cdot m^{-2}$ threshold considered by Higlett and colleagues as a limit to the luminance of LEDs.

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