Submitted to Warsaw Summer School on Advanced Optical Imaging 2024

Luminance of two-photon stimuli

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1. Main Text

Two-photon vision phenomenon is based on visual perception of pulsed infrared lasers (800-1300 nm) due to isomerization of visual pigments caused by two-photon absorption [1,2] Future applications of this effect, both in medical diagnostics and in virtual/augmented reality (VR/AR), require the ability to determine the luminance of the two-photon stimuli. However, the luminous efficiency function V(λ) outside of the visible range is unknown, requiring a non-standard approach to quantifying the luminance of two-photon stimuli. This study proposes a brightness matching method to determine the subjective luminance of two-photon infrared stimuli using photometric units, i.e., cd/m^2. Through this approach, we present the relationship between the luminance of two-photon stimuli and a novel physical quantity connected with perceived brightness: two-photon retinal illuminance. Our results predict that the luminance of a two-photon stimulus could achieve nearly 170 cd/m^2 within the safe range of laser power for the eye.

2. Methods and results

The measurements of the luminance of the two-photon stimuli by the brightness-adjustment method involved 6 healthy participants (26-46 years old; mean age 38.7) without diagnosed systemic diseases or pathologies of the visual system. The study was approved by the Bioethics Committee of the NCU. During the brightness-adjustment method, two E-letter stimuli were presented simultaneously: an infrared (IR: 1040 nm, 76 MHz, 260 fs) stimulus with a specific, constant brightness and a visible (VIS: 520 nm) stimulus whose brightness was adjusted by the subject with 0.5 dB steps. The measurement series consisted of 5 luminance matches for 8 spatial frequencies. The size of the presented stimulus ranged from 0.1° for 24 cpd to 2.5° for 1 cpd. The series of measurement were performed four times for each participant; twice with the background (10 cd/m^2), and twice without the background. The procedure enabled the determination of the power of the VIS beam, which corresponded to the brightness of a given IR beam power. Using the relationship (measured separately for the projecting system) between the power density of the VIS laser and the luminance of the projected stimuli, it was possible to determine the subjective luminance of the IR stimuli using photometric units; i.e., cd/m^2.

The luminance L of two-photon stimuli is linearly related to the *two-photon retinal illuminance* with physical units $[\frac{W^2}{m^2}]$ as described by following equation:

$$L \sim \frac{P_{IR}^2}{A_R} \tag{1}$$

where P_{IR} is power of IR beam perceived due to two-photon vision and A_R is area of illuminated retina. The relationship of the adjusted luminance of the *two-photon retinal illuminance* is shown in Figs 1 (a) and (b) for each participant in the study. The resulting values of luminance were plotted in log-log plot fashion and fitted with a linear function, where the slope of the linear fit is equal to 0.79±0.04 and 0.91±0.02 for the background-off and background-on conditions, respectively. The same data presented with different-colored symbol corresponding to a different spatial frequency of the stimulus allow to analyze how the size of stimuli affected luminance matching: Fig. 1 (c) and (d). It can be seen that smaller stimuli were presented with higher *two-photon retinal illuminance* and exhibited higher luminance. The linear fits shown in Fig. 1 (c) and (d) are calculated for non-logarithmic data. It can be seen that the weaker linearity for the fits without background (*i.e.*, slope 0.79 in Fig. 1 (a) and the bending of the straight line on the log scale in Fig. 1 (c)) is probably due to an overestimation of the luminance of the largest stimuli. This effect is not present for luminance matching against background – Fig. 1 (d). Additionally, the data obtained from measurements conducted against a background exhibit a smaller spread of the points (higher R^2 in Fig. 1 (b) and (d)), indicating overall better accuracy in the brightness matching method for two-photon stimuli under these conditions.

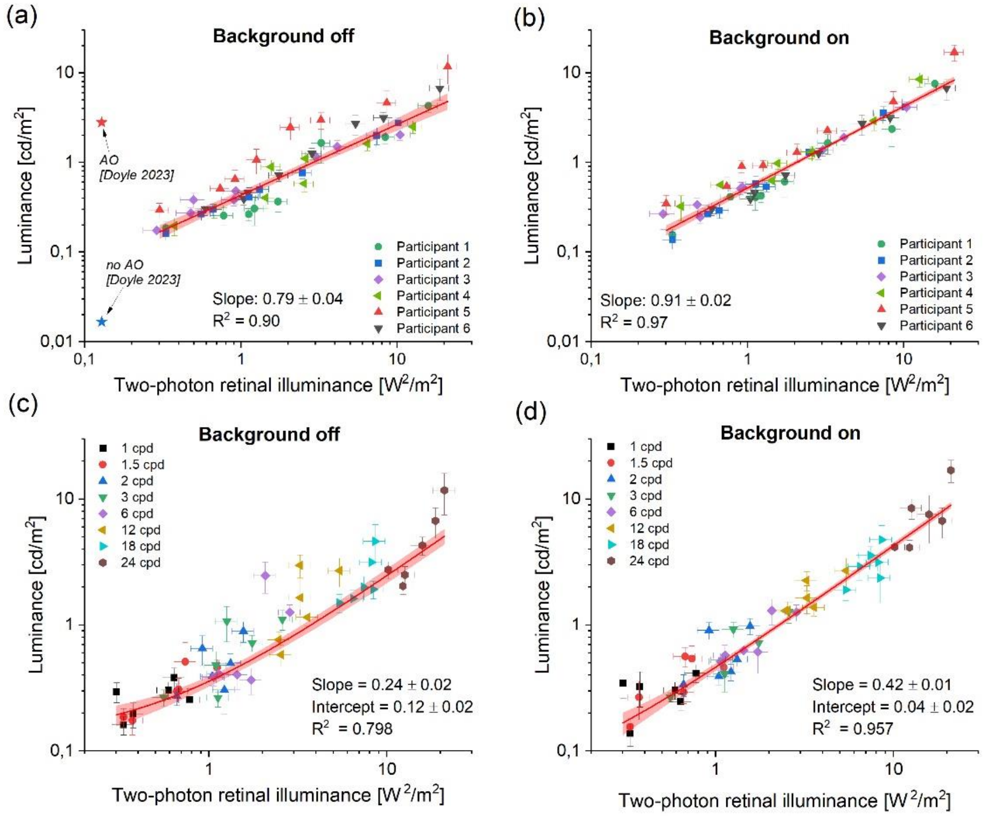

Fig. 1. Relationship between luminance and *two-photon retinal illuminance* (Eq. (5)). Luminance results are shown for each participant with the background turned off (a); and with a white background of 10 cd/m^2 turned on (b). The same data for each stimuli size are shown in (c) and (d). The symbols indicate the mean value for each participant and each stimulus size. The error bars are ΔL according to description in text below. The star indicated points on (a) are calculated based on data provided in [18]. The linear fits are indicated by red lines: to log-data (a) and (b), and to non-log-data (c) and (d). The red-colored regions are 95 % confidence intervals.

3. Funding

Foundation of Polish Science (MAB FENG 02.01).

4. References

[1] Palczewska, G., Vinberg, F., Stremplewski, P., Bircher, M. P., Salom, D., Komar, K., Zhang, J., Cascella, M., Wojtkowski, M., Kefalov, V. J., & Palczewski, K., “Human infrared vision is triggered by two-photon chromophore isomerization”, PNAS 111(50), E5445–E5454 (2014).

[2] Komar, K., “Two-photon vision – Seeing colors in infrared”, Vision Research 220, 108404 (2024).