

Color matching of two-photon stimuli projected by scanning laser

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1. Main Text

Human perception of light is traditionally considered to be restricted to the visible range of spectrum, approximately 400-700 nm. However, over several decades of working with pulsed infrared lasers, various observers have reported visual sensation when exposed to beams from outside the visible range [1]. This phenomenon, known as two-photon vision, occurs when visual pigments in retinal photoreceptors absorb two photons simultaneously through two-photon absorption (TPA) [2]. The color of beams in the range of 850–1200 nm perceived by two-photon vision corresponds to around one half of the IR wavelength, however recent work report on some irregularities [1]. This research focuses on determining the exact hue values of two-photon colors and investigating, how wavelength and brightness affect color perception. A key motivation behind this work is potential application of two-photon vision for displaying infrared content in Augmented Reality technology.

2. Methods and results

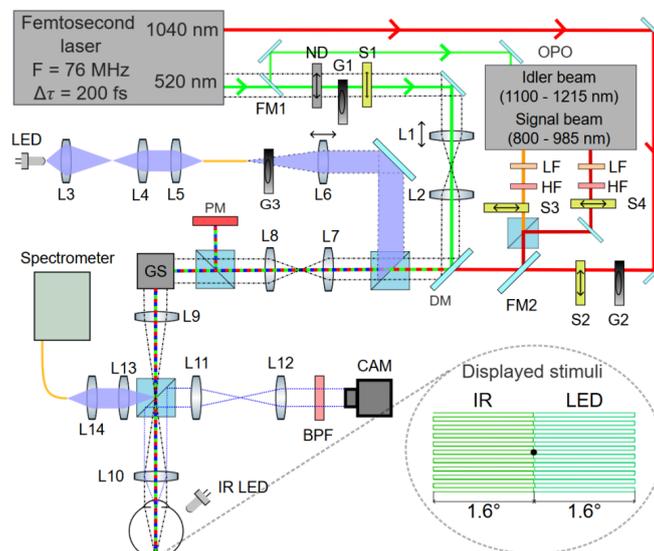


Fig. 1. Optical system. FM – insertable mirror L - lenses, S - shutters, ND – neutral, density filter, G - gradient filter, GS - galvanometric scanners, BPF bandpass filter, PM - power meter, OPO - optical parametric oscillator

On Fig 1. optical system was presented. The light source used in this experiment was 4-Wavelength High-Power LED Head (LED4D008), which provided light from 3 types of LEDs, red (655 nm), green (520 nm) and blue (450 nm). Gamut of this light source is large allowing for more correct matching of monochromatic colors, compared to previous work regarding this subject [3].

Femtotrain HighQ Laser, with temporal parameters of $F = 76$ MHz and $\Delta\tau = 260$ fs, was used for generating 1040 and 520 nm beams. For generating other wavelengths, optical parametric oscillator (OPO), with the same temporal parameters, was integrated into the system. Both signal and idler beam of the OPO were used, enabling the generation of wavelengths in the range of 800 nm – 1215 nm.

The participants' task was to adjust the brightness of each group of diodes individually to match the color produced by the diodes to the color of the two-photon stimulus presented by the IR laser. The matching was done for 11 different IR wavelengths, ranging within 800 nm – 1215 nm. In each series, 3 intensity levels of stimuli, listed in Table 1, were investigated for 5 participants (25 – 47 y.o.). The stimuli were presented side by side directly onto the subjects' retinas using galvanometric scanners. Each stimulus was a square raster with an angular size of 1.6 degrees. After the matching was done, the color matching functions [4] were used to calculate the chromacity coordinates corresponding to matched color spectrum.

The results of measurement were plotted on Fig 2A on standardized color palette "CIE 1976 UCS". The triangle marked with a dashed line indicates gamut of colors achievable by LED Head. Additionally, on Fig 2B. the difference of dominant wavelength of each point and its expected value were plotted in function of stimulating IR wavelength.

Table 1. Intensity values for each wavelengths described in retinal illuminance [5,6]

Wavelength [nm]	800	840	870	910	954	985	1040	1100	1130	1175	1215
■ Power 1 [Td]	1391	120	75	80	61	115	182	138	108	38	25
▲ Power 2 [Td]	695	59	31	30	41	48	76	58	45	11	15
▼ Power 3 [Td]	348	30	17	17	15	12	19	14	11	5	8

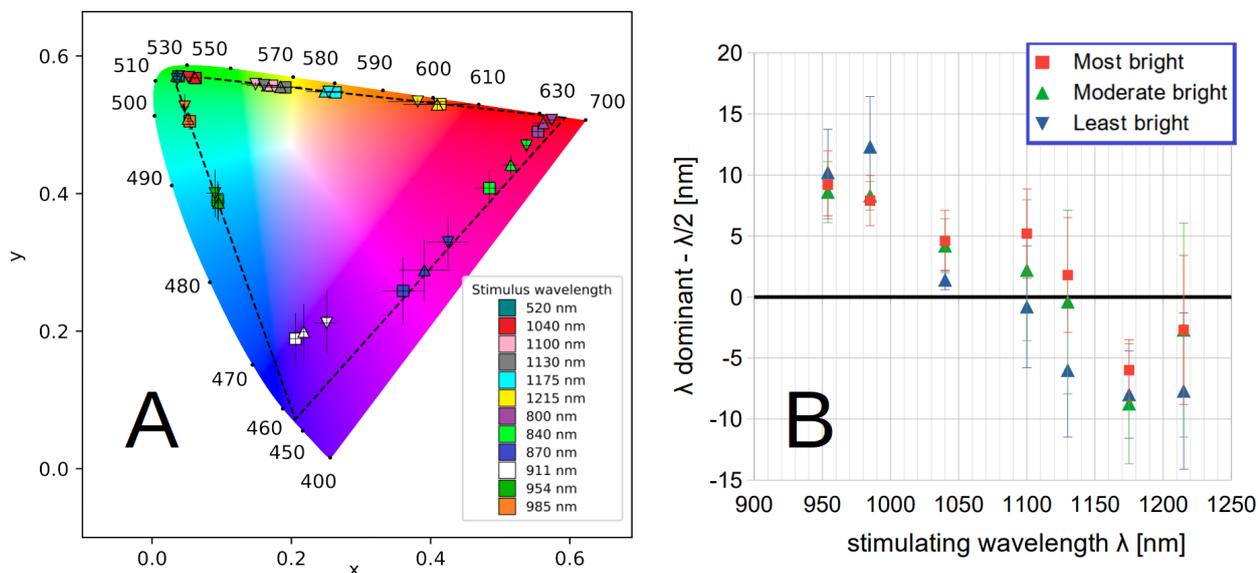


Fig. 2. A: CIE 1976 UCS chromaticity diagram with average color coordinates for all matched wavelengths and brightness levels (Table 1); B: Difference of dominant wavelength of a color and its expected value plotted in function of stimulating IR wavelength for several brightness levels.

- Most symbols are located on the edges of the LED illuminator’s gamut, indicating pure, monochromatic colors.
- Symbols for 800-870 nm are located on the purple line due to the overlapping of two mechanisms [3,7]: normal, one-photon vision (red color perception) and two-photon vision (blue color perception). The differences in hue with stimulus intensity are caused by changes in the ratio of one- and two-photon vision. This ratio shifts, because the number of two-photon absorptions changes quadratically with intensity, whereas the number of one-photon absorptions changes linearly.
- White symbols (910 nm) are distant from the edges of the illuminator’s gamut – each participant added a significant amount of green to the LED color mixture, indicating an additional process, possibly the two-photon excited fluorescence of ocular lipofuscin.
- On Fig 2B, it is apparent, that most of the two-photon colors differ significantly from their half-of-the-wavelengths counterparts. Wavelengths <1100 nm are red-shifted, while wavelengths >1100 nm are blueshifted.

3. Conclusions

The two-photon color gamut covers most of color space of normal vision, promising wide gamuts for two-photon displays. Color perception of stimulus perceived with two-photon absorption is not only dependent on wavelength, but also on the laser power. The observed differences compared to half-of-wavelength colors may be due to differences in two-photon absorption efficiency between visual pigments (S-, M-, and L-cone opsins and rhodopsin) compared to normal vision and require further investigation.

4. Acknowledgement

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