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A STUDY OF THE SUSTAINED PUPIL RESPONSE UNDER A VARIETY OF LED ILLUMINATIONS

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Abstract

The sustained pupil response of 9 observers has been recorded after 5 minutes adaptation to 5 spectrally different lights, at 100 and 210 lx. Warm white and Cool white commercial illuminations, and three metameric illuminations: incandescent light and two colour LED associations have been used. When the spectral power distribution of the light is strongly imbalanced with depletion around 480 nm, the pupil dilates more than with a smooth spectral power distribution. The phenomenon reflects the spectral selectivity of the pupil response, possibly due to weak excitation of the melanopsin retinal ganglion cells. Keywords: Pupil visual response, Melanopsin retinal ganglion cells, LED, Spectral power distribution.

1 Introduction

Melanopsin-expressing retinal ganglion cells (mRGCs) which are maximally photoreceptive around 490 nm and rods having a peak sensitivity at 507 nm, have been shown to drive the pupil response (Dacey et al., 2005; Gamlin et al., 2007; Mure et al., 2009; Markwell et al., 2010). The light emitted by white LEDs shows a peculiar spectral power distribution with a sharp spectral component in the short visible wavelengths associated with a yellow light component emitted by fluorescence. Here we investigate whether the deficit of energy of LEDs in the vicinity of 490 nm could weaken the pupillary constriction in comparison to conventional light sources of similar colour temperature.

2 Methods

2.1 Illuminations

Two commercial LED sources and three metameric illuminations have been prepared and made available in a large light booth where observers could practice reading and writing (Viénot, Brettel et al., 2012).

- Commercial „Warm White“ (WW), 2842 K
- Commercial „Cool White“ (CW), 5290 K
- Incandescent (INC), 2555 K
- WW+Amber+Green (WW-A-G-LEDs), 2561 K. In this illumination, the spectral power distribution is strongly unbalanced, with high energy content around 590 nm and strong power depletion around 480 nm.
- Multi-Colour-LEDs, 2579 K. In this illumination, the spectral power distribution that is obtained using only colour LEDs simulates at best the spectral power distribution of the incandescent light.

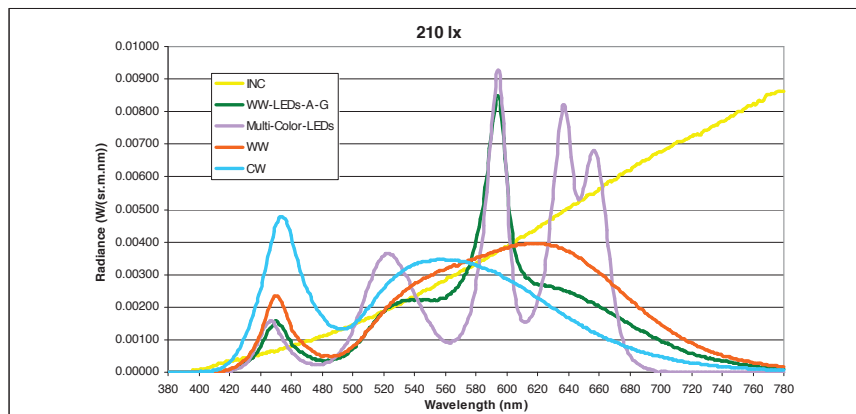


Figure 1 – Spectral power distributions measured at 210 lx

Identical relative spectral power distributions were available at 100 lux and 210 lux (Fig. 1). As a whole ten illuminations have been prepared (Table 1).

Table 1 – Illuminations: Illuminance and correlated colour temperature

	WW	CW	INC	WW-LEDs-A-G	Multi-Color-LEDs
Tcp (K), 100 lux	2849	5257	2383	2380	2404
Tcp (K), 210 lux	2842	5290	2555	2561	2579

2.2 Experiments

The study has involved 10 subjects aged 24-65 years.

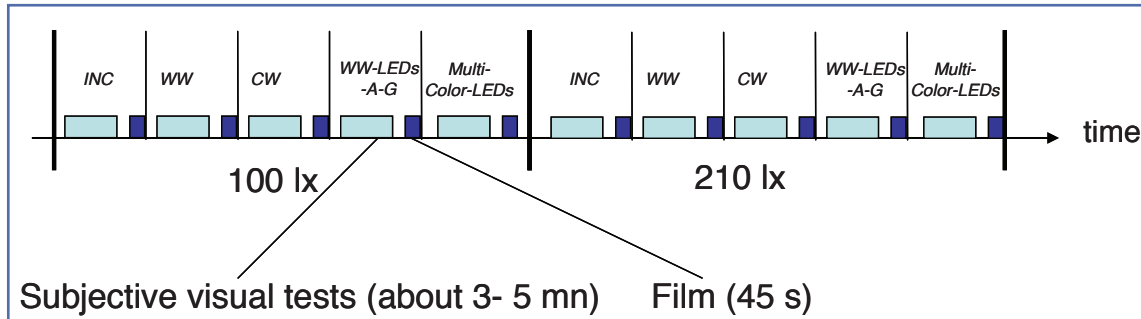


Figure 1 – Sequence of illumination blocks within one experimental session

Ten illuminations (five lights at 100 lx and 210 lx) were presented to each observer, during one session. One block of illumination started with three to five minutes of practicing subjective visual tests: near acuity at high and low contrast, reading upper-case letters printed in four size and at four contrast levels (100%, 50%, 30%, 20%), as well as rating subjective comfort (Neutral, Pleasant, Tiring, Comfortable, Glaring) on an analogue scale. Primarily, the three to five minutes practice time has been designed to allow the subject to adapt to light. Then the subject was instructed that the video recording of his eye would start and asked to gaze at the cam-recorder during 45 seconds.

2.3 Pupil measurements

An interface using ®LabView has been created to measure the pupil diameter in every view. A series of about 1100 images (45 seconds duration) was extracted from the video, close to the end of each illumination block, once the pupil aperture has stabilised. Every image of the recorded video was analysed using a specially developed program that extracts the pupil diameter, as well as the iris diameter and the spatial coordinates of the center of the pupil which were used as a control. An online control has been necessary in order to eliminate oddities (blinkings and out-of-range values).

Indeed, besides oscillations that accompany the natural pupil response, artefacts appeared as isolated or short series of measurements that differed from previous or subsequent measurements. After ordering the diameter measurements within one sequence, we manually eliminated the points at the ends of the distribution that clearly deviated from the series (Fig. 2). Only a very limited number of points had to be eliminated, compared to more than 1100 measurements within a sequence.

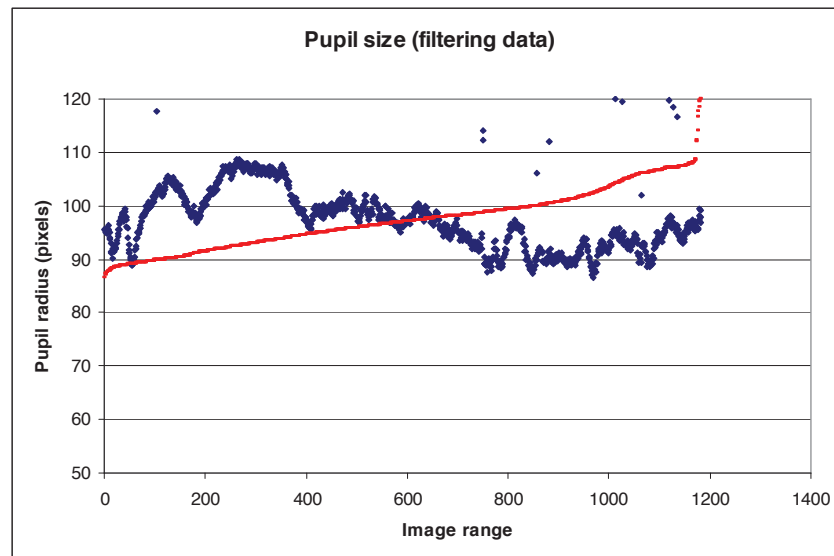


Figure 2 – Example of pupil radius measurements (in pixels). The blue curve shows the actual record. The red curve shows the ordered measurements, from which out-of range values at the two ends can be deleted.

As a whole, 110000 images (10 illuminations x 10 observers) have been screened. One observer's pupil was too dark to be safely segmented, thus the pupil measurements analysed in this paper refer only to 9 observers.

Calculation and statistical analysis have been made considering the median value of the measurements for every subject and every illumination.

3 Results

3.1 General tendency

The pupil diameter decreases with the light level (Fig. 3). The magnitude of the reduction of area A , calculated as $(1 - (A_{210}/A_{100}))$, varies between 9.7% and 38.8% among subjects. On average, there was a 29.2% reduction of area between 100 lx and 210 lx.

The cool white light constricts the pupil at most, whichever light level is used (Figure 2). In general, the higher the colour temperature rises, the more the pupil constricts. It is true for 8 out of 9 subjects. On average, there was a reduction of area A , calculated as $(1 - (A_{CW}/A_{inc}))$, between incandescent light and „Cool White“ LED light (16.0% at 100 lx and 12.1% at 210 lx), or between „Warm White“ LED light and „Cool White“ LED light, calculated as $(1 - (A_{CW}/A_{WW}))$, (17.6% at 100 lx and 15.0% at 210 lx).

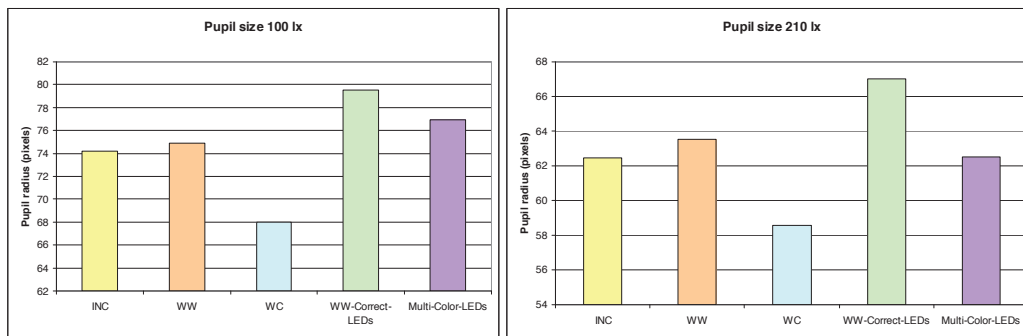


Figure 3 – Average pupil radius in the 10 experimental conditions

3.2 Effect of the spectral content

Table 2 – Illuminations: Illuminance and correlated colour temperature

		INC	WW	CW	WW-LEDs-A-G	Multi-Color-LEDs
100 lx 9 observers	Median	74.19	74.91	67.99	79.57	76.90
	Standard deviation	6.00	4.20	3.19	5.10	4.61
	Coefficient of Variation	0.08	0.06	0.05	0.06	0.06
	Average number of values	1158	1119	1145	1113	1110

		INC	WW	CW	WW-LEDs-A-G	Multi-Color-LEDs
210 lx 9 observers	Median	62.47	63.52	58.57	67.01	62.53
	Standard deviation	4.46	3.06	2.25	3.29	3.30
	Coefficient of Variation	0.07	0.05	0.04	0.05	0.05
	Average number of values	1208.78	1176.11	1209.67	1192.78	1160.67

The comparison of the three metameric lights shows that the “WW-A-G-LEDs” light leads to larger pupil dilation than does the “multi-colour LEDs” light, and that the incandescent light leads to the smallest dilation (Table 2). This effect is more obvious at 210 lux than at 100 lux. The average increase of pupil surface A between the incandescent illumination and the “WW-A-G-LEDs” illumination calculated as $((A_{WWAG}/A_{inc})-1)$ is 15.0%. Some variability is noticeable among observers. Nevertheless, the largest pupil dilation with “WW-A-G-LEDs size is observed for 8 out of 9 observers at 210 lx.

The commercial “Warm White” LED that has an intermediate colour temperature, is not as efficient as one would expect (Fig. 4). Its light dilates the pupil slightly more than the incandescent light which is of a lower colour temperature, thus contrary to expectation according to the tendency related to the colour temperature. The average pupil surface gain that follows could be estimated at 2-4% of the surface.

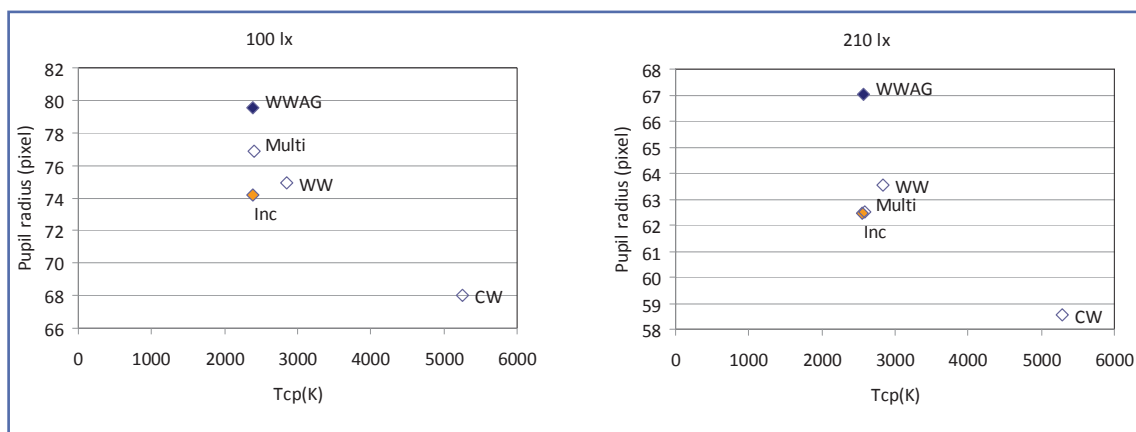


Figure 4 – Average pupil radius versus the correlated colour temperature in the 10 experimental conditions

3.3 Performance

On average, near-acuity at high contrast is good compared to low-contrast near-acuity. For most observers, near-acuity is slightly improved at 210 lx versus 100 lx, although the improvement is not significant when all observers' results are averaged. At a given contrast, near-acuity does not significantly differ neither with the choice of level nor with the choice of illuminant (Results not shown in this article).

Reading is easier with large letters, high contrast and high illuminance, than with small letters, low contrast and low luminance. In summary, our results comply with what is known from the contrast sensitivity function (Van Nes, Bouman, 1967).

With respect to subjective judgments related to comfort, no clear tendency has appeared with the exception that for all observers, the cool white illumination is generally rated as the most glaring, the most tiring and the least pleasant of all illuminations.

4 Discussion and conclusion

The reduction of the pupil size with the luminous level and with the colour temperature is a well-known phenomenon (Viénot, Durand et al., 2009).

Remarkably, the comparison of the pupil size under the three metameric illuminations reveals the influence of the spectral power distribution on the pupil response. Indeed the spectral power distribution of the "Multi-colour-LEDs" illumination as well as the "WW-A-G-LEDs" illumination which dilate the pupil unnaturally are unusual lighting situations, the latter, which is strongly unbalanced, probably reflecting an unlikely extreme case.

Whereas careful stabilisation of the pupil response has been achieved through allowing for a three minutes adaptation time and eliminating eye blinking measurement and out-of-range measurements, we cannot ignore that the pupil aperture is under the effect of individual parameters including age. The origin, frequency and magnitude of inter-individual variations of the spectral selectivity of responses deserve further study. Nevertheless, the reduction of the pupil size with the luminous level, with the colour temperature and with the deficit of energy around 480 nm has been observed for most observers at 210 lx.

It is probably the amount of energy available in this wavelength range that favours the pupil constriction. Because the spectral power distribution of the LED associations shows depletion around 480 nm, it could well reflect the role of the Melanopsin-expressing retinal ganglion cells (mRGCs) which are maximally photoreceptive around 490 nm. The observation that, in our experimental conditions, the "Warm White" LED illumination slightly dilates the pupil more than the incandescent light does might also be linked to the energy deficit of the spectrum around 480 nm.

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