PLOS ONE | DOI:10.1371/journal.pone.0147464 January 27, 2016

RESEARCH ARTICLE

# Human Visual System as a Double-Slit Single Photon Interference Sensor: A Comparison between Modellistic and Biophysical Tests

Rita Pizzi*, Rui Wang, Danilo Rossetti
Department of Computer Science, University of Milan, Milan, Italy

* rita.pizzi@unimi.it

## Supporting Information

# S1 Appendix

## Choice of LED and Optical Filter

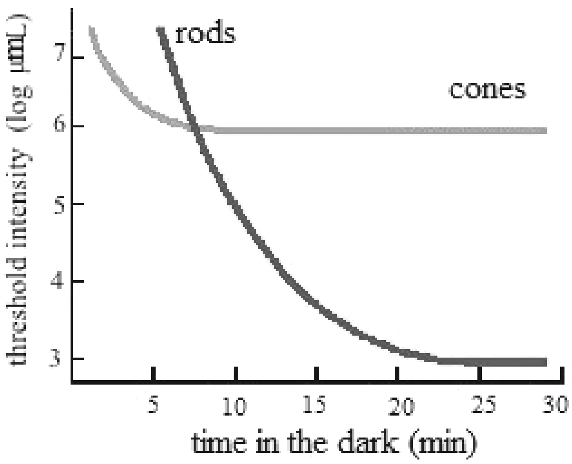
The choice of the LED source was based on the need to limit the coherence length of the photons emitted within the short space available between the source and the eye. Indeed, we were interested in imagining that the entire wavelength of the photon reached the eye. The coherence length of a typical NICHIA LED is of micrometer order, with a coherence time, $\tau_{coh} = \frac{L_{coh}}{c}$ (where $L_{coh}$ is the coherence length (see Appendix 2) and $c$ is the speed of light), of picosecond order. An LED wavelength of 520 nm was chosen, because eye functionality at maximum sensitivity under dark conditions requires activation of the rods that have the highest sensitivity to a wavelength of approximately 500–520 nm [1]. The classic slow-phase adaptation curve shows the change in sensitivity as a function of time [2,3] (S1 Fig).

However, a recent work [4] notes a number of biases in previous measurements and illustrates the methodological correctness of the most recent theoretical and empirical measures. The result is the presence of multiple peaks of maximum sensitivity for scotopic vision, along with a general increase in the range of wavelengths with several peak values, having a maximum at approximately 540 nm (S2 Fig).

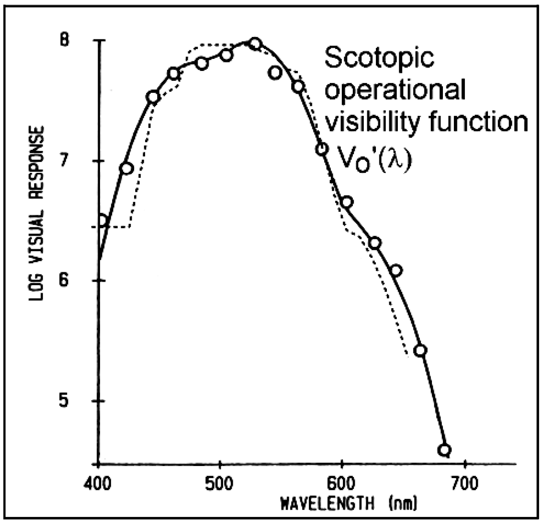
These findings led us to choose a filter to further reduce the number of photons incident on the eye, and aided us in selecting a suitable frequency for the experiment. Ultimately, we chose the OptoSigma filter mentioned in the Materials and Methods section.

## Photomultiplier Characteristics and Measurements

The photomultiplier used in the experiment was a Hamamatsu Photonics (Hamamatsu, Japan) [5] R 212 device, provided with an Amptek, Inc. (Bedford, MA) A-111 preamplifier-discriminator and a programmable counter PC05 TESYS (Trezzano, Italy) [6,7]. A Tektronix, Inc. (Beaverton, OR) 2245A 100MHz oscilloscope [8], was also used during the experiment. The photomultiplier was set according to the manufacturer's specifications to a bias scheme of 760 V, and was tuned to the minimum LED intensity, which was established as 61.8 μA, as explained below. Taking into account the $Q_e$ of 4% reported by the manufacturer, the average number of photons/s after a series of measurements appeared to be 433.33 (99% confidence interval [387.32, 499.33]. The dark count was 7.5 shots/s, which was a properly limited value.




**S1 Fig. Classic slow-phase adaptation curves.** After approximately 20-min exposure to dark conditions, the rods achieve maximum sensitivity.




**S2 Fig. Maximum sensitivity for scotopic vision (from [4], p. 168).** Overlay of measured data (solid line with experimental values) with theoretical prediction (dotted line).

## References


1. Burle Electron Tubes. Electro-optics Handbook. Burle Electron Tubes; 1974.
2. Graham CH. Vision and visual perception. New York: John Wiley and Sons, Inc.; 1965.
3. Hecht S, Schlaer S, Pirenne MH. Energy, quanta and vision. J Opt Soc Am 1942;38: 196-208.
4. Fulton JT. Processes in biological vision. Vision Concepts. 2014. Available: http://neuronresearch.net/vision/pdf/17Performance1a.pdf#page168.
5. Hamamatsu Co. Photomultiplier Tubes. Available: http://www.hamamatsu.com.
6. Amptek Co. Charge sensitive preamplifiers. Available: http://www.amptek.com/hybrid-selection-guide/.
7. Tesys Technology & Systems SAS. Programmable Counters. Available: http://www.tesyslab.eu/en/8-programmable-counters-counting-systems.
8. Tektronix Inc. Oscilloscopes. Available: http://www.tek.com/oscilloscope#all.

# S2 Appendix

## Bunching Problem

A Poisson process with a rate of $\lambda$ is a counting process, $\{N(t) \mid t \geq 0\}$, that possesses, among other characteristics, the property that the number of event occurrences counted within disjoint intervals are independent of each other. In fact, photons are completely uncorrelated (apart from coherent light) and temporal coherence indicates a monochromatic source. This is determined from the spectral width, $\Delta\nu$, where

$$\tau_{coh} \cong \frac{1}{\Delta\nu} \quad . \tag{10}$$

This is because $L_{coh}$, during which light oscillates at the point of irradiation, has a regular and strongly periodic character. Here, $\Delta\nu$ is the spectral width (full width at half maximum) of the beam (in Hz). As light propagates at a rate of $c = 3\times10^{11}$ mm/s, the light oscillations are matched by the phase (i.e., they are coherent) over the length of the light propagation, $L_{coh}$ (the measure of temporal or longitudinal coherence), such that

$$L_{coh} = c\tau_{coh} = \frac{c}{\Delta\nu} . \tag{11}$$

The more monochromatic the light, the longer the length for which the light field is coherent in volume. For a single-mode (single-frequency) He-Ne laser ($\lambda$ = 632.8 nm), $L_{coh}$ >> 1 m.

As we did not use a laser source in this study, but instead applied an LED source that can be considered to be halfway between a perfect laser source and a thermal light [1-3], we must consider the possibility that photon bunching occurred [4,5]. Further, the photons may have followed a Bose-Einstein distribution (instead of a Poisson distribution), where

$$P(n) = \frac{<n>^n}{(1+<n>)^{1+n}} \ . \tag{12}$$

Here, if $<n>$ is the average number of photons per pulse, then

$$<n> = \sum_{n=0}^{\infty} nP(n) \ . \tag{13}$$

It must be noted that photon bunching can only be observed if the sampling time is much shorter than $\tau_{coh}$ [6]. This is because the light can no longer be considered to be monochromatic, if the observation time interval is comparable to or greater than $\tau_{coh}$. From the semi-classical perspective, the light intensity fluctuates randomly with the typical duration of the fluctuations, of the same order as $\tau_{coh}$. If a photon is detected within a small time interval, $\Delta t$, inside the field sampling time, $T_{\text{int}}$, it is more likely that another photon will be detected within $\Delta t$. However, if $T_{\text{int}}$ is greater than $\tau_{coh}$, a single mode will not be observed and the Bose-Einstein distribution has no application. The photon-count distribution then becomes the Poisson distribution. To avoid doubts that a Bose-Einstein distribution could emerge in our experiment, we wished to evaluate the $\tau_{coh}$ of our light source. For an LED emitting at $\lambda$ = 510 nm ($2\times10^4$ cm$^{-1}$), for example, $\Delta\lambda$ = 37.3 nm ($2.7\times10^5$ cm$^{-1}$). Green LEDs (in particular NICHIA LEDs) are reported to have $L_{coh}$ $\cong$ 4 μm and $\Delta\lambda \cong 30$ nm [7,8]. The $\tau_{coh}$ of our NICHIA LED was, therefore, of picosecond order. As $T_{\text{int}}$ for the human eye can be set to the order of milliseconds, this means that Bose-Einstein distribution conditions were not applicable.

On the other hand, [9] shows that faint non-Poissonian sources with ultra-low mean photon numbers can be treated as being approximately Poissonian. In any case, in this study, a bunching condition was not an impediment to obtaining a possible experimental outcome, as we aimed to simulate the perception of interruptions in the photon stream. Such events are not prevented by the presence of photon bunches in the stream.

## References


1. Woodward E. Photon counting statistics for two characteristic light sources. PhD Thesis, Rochester Institute of Technology. 2008.
2. Martinez Ricci ML, Mazzaferri J, Bragas AV, Martinez OE. Photon counting statistics using a digital oscilloscope. Am J Phys 2007;75: 707.
3. Mehta S, Saxena K, Dubey SK, Shakher C. Coherence characteristics of light-emitting diodes. JOL 2010;130(1): 96-102.
4. Hanbury Brown R, Twiss RQ. Interferometry of the intensity fluctuation in light. I. Basic Theory: the correlation between photons in coherent beams of radiation. Proc R Soc A 1957;242(1230): 300-324.
5. Purcell E. The question of correlation between photons in coherent light rays. Nature 1956;178(4541): 1046-1048.
6. Fry TC. Probability and its engineering uses. New York: Van Nostrand. 1929.
7. Kocayk P, Wiewior P, Radzewicz C. Photon counting statistics. Am J Phys 1996;64(3): 240-245.
8. Stuerwald S, Kemper B, Remmersmann C, Langehanenberg P, von Bally G. Application of light emitting diodes in digital holographic microscopy. Proc of SPIE 2008;6995: 699507-2008.
9. Hu Y, Peng X, Li T, Guo H. On the Poisson approximation to photon distribution for faint lasers. Phys Lett A 2007;367: 173-176.