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# Modeling Luminance Perception at Absolute Threshold - Supplemental Materials

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**Abstract**

*This is a supplemental text for the EGSR 2015 paper submission ID 1000. It provides additional information about details form the paper. Please refer to the index.html or readme.txt for more details about the provided video and image gallery as well as distribution sampling lookup tables.*

## 1. Photon counting

Near absolute threshold, the absolute number of photons becomes important and we derive a per-receptor estimate in this section.

First, we assume that the HDR input image contains scene-referred calibrated values in CIE XYZ color space (refer to [RWD*10, Table 2.9] for transformations from/to other standard RGB color spaces). The derivation is independent between pixels and described for a single pixel in the following.

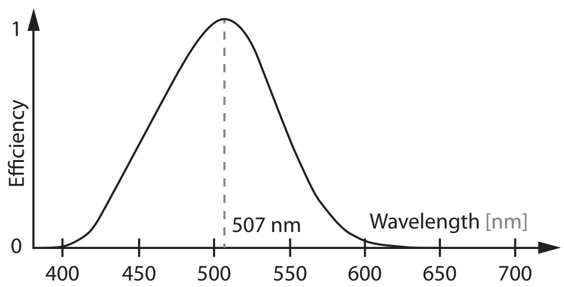


**Figure 1:** *The scotopic luminous efficiency function [Wan95].*

Given a pixel, its HDR XYZ values are converted into scotopic luminance $L$ following the transformation proposed in [PFFG98]:

$$L = -0.702X + 1.039Y + 0.433Z.$$

Note that this is merely an approximation derived through a linear regression of the color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ and the scotopic luminous efficiency function $V'(\lambda)$ [Wan95] (see Fig. 1), which are defined over the visible spectrum of wavelengths $\lambda$. In an unlikely case when per-pixel spectral radiance values $Y_e(\lambda)$ are available (as in [KO11]), $L$ can be computed directly as:

$$L = 1700 \int_0^\infty V'(\lambda) Y_e(\lambda) d\lambda. \tag{1}$$

In both cases, a scotopic luminance $L$ in candela per square meter is obtained. Given the area $\Delta A$ of a screen pixel, the scotopic luminous intensity in candela is $I = \Delta A \cdot L$. The luminous flux $\Phi_s = I \cdot \Delta\omega$ arriving at the retina is expressed in lumen, where $\Delta\omega$ is the solid angle of the pupil. This solid angle $\Delta\omega = 2\pi \cdot d_p (d_p{}^{-1} - (d_p^2 + d_s^2)^{-1/2})$ is approximated as a disk of diameter $d_p$ in distance $d_s$. The distance to the pupil $d_s$ is given by the distance of the observer to the display. The diameter of the pupil $d_p$ depends on the luminance adaptation state and can be computed for the average value of $L$ [WY12].

The data we use in Sec 5.2 of the main paper were acquired for $\lambda$ = 507 nm [HSP42], the peak of $V'$. We assume that the response to other wavelengths close to absolute threshold is proportional to their luminous efficiency (refer to Eq. 1). In other words, we treat multi-chromatic luminous flux $\Phi_s$ as equivalent to its monochromatic analog with $\lambda$ = 507 nm. Therefore we can derive the radiant flux $\Phi_e$ in Watt as: $\Phi_e = \Phi_s/1700$, i. e., by inverting Eq. 1, which holds for any photometric quantity and its radiometric counterpart. The radiant energy for a time interval $\Delta t$ in Joule is $Q_e = \Phi_e \cdot \Delta t$. The energy of single photon in Joule is $E = \hbar c/\lambda_s \approx 3.918 \cdot 10^{-19}$, where $\hbar$ is the Planck constant, $c$ the speed of light and $\lambda_s$ = 507 nm the wavelength of the theoretically luminance-equivalent monochromatic source. Finally, the number of photons entering the pupil is $P = Q_e/E$.

To determine the number of rods that are covered by a pixel projection, we assume that a 24" display with 1920×1200 pixels is observed from the distance $d_s$ = 0.6 m. We also assume a density of 100,000 rods / mm$^2$. We chose this value as a representative average density, since the rod acuity peak has a density of 150,000 rods / mm$^2$ [JSN92] at the eccentricity of 1.5 mm from the fovea center [MKN84].

Based on these assumptions and knowing that the spatial extent of one visual degree corresponds to approximately 0.288 mm on the retina [DF74], we derive that roughly $\rho =$ 5 rods are covered by each pixel. Given an ideal optical focus each rod can only see a single pixel. Therefore no additional compensation such as number of visible pixels has to be considered. Further, assuming a perfect focus in the eye optics, the number of photons per rod can be approximated as $N_r = P/\rho$.

As our model is fitted for a retinal area covering 500 rods, we set the coefficient $\phi$ for the conversion from the input HDR luminance $L$ to the photon count $N$ as $\phi = 500 \cdot N_r$, hence $N = \phi L$. Using our setup $\phi \approx 1.2 \cdot 10^5$ for $10^{-3}$ cd / m$^2$.

## 2. User study

### 2.1. Motivation

Introducing artifacts in images or videos can be useful for artistic purposes. Considering that a large number of artifacts are intentionally introduced in almost all movies or games – such as depth-of-field, motion blur, glare, and in particular the addition of noise (e.g. the motion pictures Hugo, 300, Pi, Planet Terror, Saving Private Ryan or the game Limbo) – it is clear that there is a substantial artistic demand. Ultimately, it is up to the artist to decide if noise should be included. But in case noise is desired, our work is first to explain how to include it properly and its cause. This is why our study focuses on comparison of four possible methods for simulation of the scotopic noise rather than answering the question whether any presence of noise is subjectively preferred by our particular subjects.

### 2.2. Instructions

Here we provide instructions that subjects of our user study read before the experiment:

In this experiment, we are interested in the noise in human vision in very dark illumination conditions (e.g. forest at night).

You will always be presented by a pair of images. Imagine that each depict a scene which you observe at very dark illumination. Focus on properties of the noise - how it looks, how does it change with image brightness, how does it behave in time.

For each of three following criteria select the better of both images:

1) Realism - which one looks more like really looking at it at night?

2) Comfort - which one is more comfortable to look at, e.g. in a movie/game.

3) Overall preference - which one would you prefer, e.g. in a movie/game, to depict night scene and maintain pleasant quality. Combine both previous criteria or use your own.

Please tell us answer for each of the three questions and then move to the next pair.

### 2.3. Detailed results

The results presented in the paper summarize the user responses over all presented stimuli. In this section we provide analysis for individual stimulus. Table 1 shows that our method is performing the best in the computer graphics stimuli (ARCHITECTURE and TUNNEL). This confirms that the advantages of our model are most prominent in combination with dynamic content while noise application to a static image is more forgiving (CAR and COUNTRYSIDE).

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| Stimuli | Comparison | Realism | Comfort | Preference |
|---|---|---|---|---|
| ARCHITECTURE | Ours dyn. × White dyn. | ⋆ 0.85 CI [0.23, 0.12] | ⋆ 1.00 CI [0.17, 0.00] | ⋆ 0.95 CI [0.20, 0.05] |
| | Ours dyn. × Ours stat. | 0.65 CI [0.24, 0.20] | 0.55 CI [0.23, 0.22] | 0.65 CI [0.24, 0.20] |
| | Ours stat. × White stat. | 0.60 CI [0.24, 0.21] | ⋆ 0.80 CI [0.24, 0.14] | ⋆ 0.75 CI [0.24, 0.16] |
| CAR | Ours dyn. × White dyn. | 0.30 CI [0.18, 0.24] | ⋆ 0.20 CI [0.14, 0.24] | ⋆ 0.25 CI [0.16, 0.24] |
| | Ours dyn. × Ours stat. | 0.65 CI [0.24, 0.20] | 0.55 CI [0.23, 0.22] | 0.65 CI [0.24, 0.20] |
| | Ours stat. × White stat. | ⋆ 0.20 CI [0.14, 0.24] | ⋆ 0.15 CI [0.12, 0.23] | ⋆ 0.15 CI [0.12, 0.23] |
| COUNTRYSIDE | Ours dyn. × White dyn. | 0.60 CI [0.24, 0.21] | ⋆ 0.75 CI [0.24, 0.16] | ⋆ 0.75 CI [0.24, 0.16] |
| | Ours dyn. × Ours stat. | 0.70 CI [0.24, 0.18] | 0.40 CI [0.21, 0.24] | 0.60 CI [0.24, 0.21] |
| | Ours stat. × White stat. | ⋆ 0.85 CI [0.23, 0.12] | ⋆ 0.75 CI [0.24, 0.16] | 0.70 CI [0.24, 0.18] |
| TUNNEL | Ours dyn. × White dyn. | 0.55 CI [0.23, 0.22] | ⋆ 0.95 CI [0.20, 0.05] | ⋆ 0.95 CI [0.20, 0.05] |
| | Ours dyn. × Ours stat. | ⋆ 0.75 CI [0.24, 0.16] | 0.60 CI [0.24, 0.21] | 0.65 CI [0.24, 0.20] |
| | Ours stat. × White stat. | 0.60 CI [0.24, 0.21] | ⋆ 1.00 CI [0.17, 0.00] | ⋆ 1.00 CI [0.17, 0.00] |
| All | Ours dyn. × White dyn. | 0.57 CI [0.12, 0.11] | ⋆ 0.72 CI [0.11, 0.09] | ⋆ 0.72 CI [0.11, 0.09] |
| | Ours dyn. × Ours stat. | ⋆ 0.69 CI [0.11, 0.10] | 0.53 CI [0.11, 0.11] | ⋆ 0.64 CI [0.12, 0.10] |
| | Ours stat. × White stat. | 0.56 CI [0.12, 0.11] | ⋆ 0.68 CI [0.11, 0.10] | ⋆ 0.65 CI [0.11, 0.10] |

**Table 1:** *Study results with relatives scores and 95 % confidence intervals (CI) for individual stimulus. Scores above* 0.5 *mark the first noise to be perceived as better according to the given criteria. Stars denote statistical significance ($p < .05$ binomial test).*