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Simulating imaging systems: Photons, parts and people

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Introduction

Investigators in many fields, ranging from image compression to visual neuroscience, are analyzing statistical properties of image data. In most cases, the analysis begins with a sample of digital image data – such as data provided in a database of gray scale images [1]. The data are then analyzed for statistical regularities that are used to build image quality metrics [2] or systems to understand the behavior of neurons in the visual pathways [3].

Digital images are neither an accurate representation of the physical scene radiance nor an accurate measure of the pattern of light that impinges on the human retina. It is now possible to use conventional devices to acquire estimates of the scene radiance [4, 5] and begin analyses of images from a description of the scene radiance. It is also possible to estimate the spectral irradiance image at the surface of the retina from the scene irradiance [6]. Finally, recent advances in technology and modeling enable us to make reasonable and quantitative estimates of the statistics of the cone absorptions across a range of conditions and to create sample mosaics that capture the basic statistics of the fovea and near periphery [7, 8].

Building on this knowledge, we developed a simulation tool that enables investigators to estimate the mosaic of cone photoreceptor responses to any image specified as a scene radiance. Our simulations are implemented as a Matlab toolbox [9], and the code can be downloaded from the web [10].

In this talk, we describe our implementation and provide examples of how the properties of an image are transformed by the human optics. We conclude by describing the progress we have made on extending the simulation from estimating cone responses to responses of visual neurons.

The visual system evaluation toolbox (VSET)

We describe briefly the principles of the simulations.

Scene radiance

The simulation input is the scene radiance along with a specification of the distance from the lens to each point in the radiance field, and an estimate of the scene illumination. The scene radiance function is required. When the distance is not known, we assume that all scene points are equi-distant and far from

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the lens. When the illuminant is not known we assume that the illuminant radiance is Lambertian with equal energy across wavelengths.

To reduce the size of the data representation, the scene radiance data are represented using linear models [11-13]. Typical wavelength sampling is 10 nm, though this value and the range can be specified by the user according to the available data.

Retinal irradiance

Scene radiance is converted to retinal irradiance using a model of the human optics. The model is implemented as a shift-invariant transform applied to each of the wavelength images in the scene radiance. They default convolution kernel is the one derived by Marimont and Wandell [14]. The software is constructed so to permit substitution of alternative wavelength-dependent kernels, say functions derived for a specific observer using adaptive optics [8]. It is also possible to specify a ray-trace calculation in which the point spread function changes with field height [15].

Cone absorptions

Cone absorptions are calculated using the Stockman absorption functions; estimates of the lens transmittance and macular pigment density are included and can be adjusted to model different types of subjects [16]. The spatial distribution and relative sampling densities of the cone types within the mosaic can be controlled, although the set of possible positions of the cones is constrained to fall on a rectangular sampling grid (with empty grid positions allowed). The cone optical aperture can be varied and the default is set to 2.5 um. The Poisson statistics of the absorptions are included, and intrinsic photoreceptor noise can be specified [17, 18].

Cone absorptions can be calculated on an arbitrary time-scale: one millisecond is the default.

Summary

The interest in the spatial statistics of the signal encoded by the eye motivated us to assemble and distribute software for calculating the retinal irradiance and cone absorptions of scene radiance. We hope that this simulation will provide a more realistic approximation of the statistical properties encoded by the nervous system. The statistics of the retinal irradiance image is significantly different from the scene radiance, and the cone absorption properties add further complexity. By making it simple to account for optical and retinal factors, we hope to enable new experimentation and insights.

In our future work, we are starting to create new simulations that convert the estimated cone absorptions into a time-varying signal that represents the cone output voltage. This stimulated cone output voltage can be used, in turn, as input to a simulation of other retinal cells [19] [20]. We hope to use these simulations as a basis for quantitative modeling of brain activity [21, 22].

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