Modeling Emmetropization in an Incessantly Moving Eye

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Many questions remain unanswered regarding emmetropization, the process by which, during development, the eye adjusts itself so that distant objects are in focus. Research has so far primarily focused on the spatial cues present in the image on the retina, such as the degree of blur. However, eye movements are always present in the fixation periods in which visual information is acquired and processed. Small saccades (microsaccades) separate periods of incessant eye jitter (ocular drift) that shifts the stimulus by many receptors on the retina [1]. These movements results in speeds of retinal image motion that would be immediately visible if generated from the motion of objects in the scene, rather than the eyes themselves.

Although frequently ignored by vision scientists, fixational eye movements transform a mostly static external scene into temporal modulations impinging onto retinal receptors. The characteristics of these modulations depend on the dynamics of eye movements, the shape, size, and optics of the eye, and the statistics of the visual scene. Consider for example, a Brownian motion model of eye drift, a model that obeys the diffusion equation:

$$\frac{\partial q}{\partial t} = D\nabla^2 q \quad \rightarrow \quad G(\mathbf{k}, \omega) = \frac{2|\mathbf{k}|^2 D}{|\mathbf{k}|^4 D_B^2 + \omega^2}$$

where $q(\mathbf{x}, t)$ represents the probability that the eye rotated by $\mathbf{x}$ in the interval t, and D is the diffusion constant that regulates the amount of jitter. This model predicts that, at each spatial frequency $\mathbf{k}$, the power of the external stimulus gets redistributed across non-zero temporal frequencies (ω) with gain G that increases up to a critical spatial frequency $k_c = \sqrt{\frac{\omega}{D}}$ and then decreases [2]. Note that below k_c, the gain of ocular drift counterbalances the k^{-2} spectral density of natural scenes, yielding equalized (whitened) power on the retina.

Because of this specific redistribution of power, the fixational modulations of luminance resulting from eye jitter provide possible cues for emmetropization. In the developing eye, the bandwidth of equalized temporal power expands as the eye approaches emmetropization and narrows as the eye moves away from it. Furthermore, the level of equalized power depends on the size of the eye, because the separation between the optical nodal points and the eye center of rotation (as well as deviations from spherical geometry in the retina) alter the amount of jitter of the retinal image (the D on the retina). Thus, the specific combination of level and extent of whitening depends on both the amount and direction of optical blur. An interesting implication of this idea is that these cues would be wrongly interpreted in the presence of abnormal eye movements, as D depends on the amount of eye jitter. Fixational eye movements are rarely considered in research on myopia, and it is presently unknown whether these cues play a role in emmetropization.[1]

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