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Modeling the role of fixational eye movements in real-world scenes

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ABSTRACT

Our eyes never remain still. Even when we stare at a fixed point, small involuntary movements take place in our eyes in an imperceptible manner. Researchers agree on the presence of three main contributions to eye movements when we fix the gaze: *microsaccades*, *drifts* and *tremor*. These small movements carry the image across the retina stimulating the photoreceptors and thus avoiding fading. Nowadays it is commonly accepted that these movements can improve the discrimination performance of the retina. In this paper, several retina models with and without fixational eye movements were implemented by mean of *RetinaStudio* tool to test the feasibility of these models to be incorporated in future neuroprostheses. For this purpose each retina model has been stimulated with natural scene images in two experiments. Results are discussed from the point of view of a neuroprosthesis development.

1. Introduction

Our eyes are always in constant motion. Some of these movements are involuntary and appear even when we fix our gaze. Although some of them are relatively large and displace the image across the retinal photoreceptors, they are not perceptible to us [1]. Since the late 1800s, several research groups have been investigating in understanding the role of these fixational eye movements in the vision [2] using a variety of techniques for recording [3]. Nowadays, the most accepted idea about the role of these movements is that they can improve discrimination performance in ways not explicable just by prevention of visual fading [4–7]. In particular, *microsaccades* are probably the eye movements with the greatest potential to perform this task [8–10].

Various approaches have been proposed to study fixational movements. On one hand, Ditchburn et al. [11], Nachmias et al. [12] and others used recording techniques to proof the role of these eye movements in visual perception. On the other hand, simulation of *microsaccades* were used to asses in a realistic manner the role of eye movements in the primary retinal responses. Greschner et al. [13] in their work performed an experiment which demonstrated that the simulated small movements, like *tremor*, in a turtle retina, activated sets of retinal ganglion cells in a synchronized manner. Finally, the approach based on retina models has several advantages from the point of view of experimentation. Comparing to an *in vivo* experimental setup, retina models can be easily modified and used as often as desired without the need of laboratory animals or annoying human testing. Moreover, retina models increase the range of possibilities, allowing for example, the description of diseased retinas, different isolated properties and more features that could not be done with biological retinas. In this way Donner and Hemilä [14] attempted to clarify the effects of these movements on the messages that retinal cells send to the brain by means of mathematical models. Also, it is remarkable that the work by Wohrer et al. [15] and Martínez et al. [16] focused primarily on the development and implementation of new retina models.

Our group is working on the development of a cortical visual neuroprosthesis aimed to restore some functional vision to profoundly visual-impaired people. For this purpose, the objective of the current study is to test the feasibility of fixational eye movements to be implemented in a visual neuroprosthesis. In this way, different retina models with and without fixational eye movements have been described and tested to check the vision improvement. Results show that retina models including eye movements have a better behavior than models without this feature.

2. Retina model

The retina plays an important role in visual perception of humans. It is responsible for converting the outside world images into electrical signals understandable by the visual cortex of the brain. In fact, it is considered as a part of the brain. This process

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must be unequivocal and fast enough to ensure recognition of objects within a few milliseconds [17]. Therefore a good retina model, as well as its physical implementation, should take into account this time constraint to be able to respond to stimuli in real time.

In this paper several retina models which are sensitive to variations in luminance are described by mean of *RetinaStudio* [18], a framework to encode visual information that allows the specification, testing, simulation, validation and implementation of bioinspired retina models. Each retina model is defined as a matrix of different kinds of ganglion cells. Models of *On* ganglion cells and *Off* ganglion cells, with and without fixational eye movements, are described making a total of four different retina models: *On* model, *On+eye movements* model, *Off* model and *Off+eye movements* model.

RetinaStudio allows us to describe the different stages that comprises a biological retina. The first stage, inspired in the *Outer Plexiform Layer* of the retina, was modeled by splitting the incoming images into three color channels (R, G and B). The second stage, inspired in the *Inner Plexiform Layer*, was modeled by means of spatial filters. More specifically, with a network of the well-known *Difference of Gaussian* (*DoG*) filter, where σ_1 and σ_2 take the values 0.9 and 1.2 respectively in the *On* retina models and take 1.2 and 0.9 values in *Off* retina models

$$DoG(x,y,\sigma_1,\sigma_2)=\frac{1}{\sqrt{2\pi\sigma_1^2}}e^{-(x^2+y^2)/2\sigma_1^2}-\frac{1}{\sqrt{2\pi\sigma_2^2}}e^{-(x^2+y^2)/2\sigma_2^2} \quad (1)$$

The magnitude value of these parameters has already been studied in the work of Morillas et al. [19]. The *Difference of Gaussian* filter receives contributions of the three types of photoreceptors R, G and B (for red, green and blue), and thus generates a *mexican-hat* contribution for every color channel. This contribution simulates the circular shape and the antagonist center-periphery behavior of the receptive fields of ganglion cells in the retina, see Fig. 1. Finally, inspired in the Ganglion Cell Layer, the *Leakage-Integrate & Fire* spiking neuron model proposed by Gerstner and Kistler [20] is used to model the ganglion cell firing behavior.

All retina models represent a piece of fovea having a size of 1.8×1.8 mm, where each receptive field is about 180 μm of diameter [21].

2.1. Eye movements

The three main contributions of involuntary eye movements were integrated within our retina models: *tremor*, *drifts* and *microsaccades*.

2.1.1. Tremor

Tremor is the amplitude-smallest of all eye movements. It consists in an aperiodic oscillation of the eyes with small amplitudes and frequencies within the range of the recording system noise [22]. Following the work of Ratliff and Riggs [3], these movements are described in our model as oscillatory waves with a small amplitude. More specifically the amplitude is in the range between 2.83 μm and 4.13 μm, and the frequency is 50 Hz. The generated oscillatory waves are superimposed on *drifts*, see Fig. 2.

2.1.2. Drifts

Drifts are slow curvy motion that occurs between *microsaccades* and appear simultaneously with *tremor*. This movement can displace the image across a dozen photoreceptors with a mean speed of 6 arcmin/s [2]. *Drifts* are described using the *gamma* distribution of Eq. (2) as proposed by [23]. In our case, $\lambda=1$ and different k values are randomly chosen taking integer values between 1 and 9. The angle of these *drifts* is randomly modified using Eqs. (3), taking into account that all *drifts* must be directed outwards [24]

$$f(x)=\lambda e^{-\lambda x}\frac{(\lambda x)^{k-1}}{(k-1)!} \quad (2)$$

$$x'=x\cos(\theta)-y\sin(\theta)$$
$$y'=x\sin(\theta)+y\cos(\theta) \quad (3)$$

In our model each drift movement has a duration between 0.24 s and 0.48 s, with a mean of 0.36 s, and an amplitude between 68 μm and 100 μm, with a mean of 84 μm. The values of duration and amplitude were randomly chosen within these ranges.

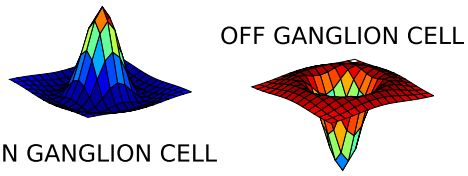

Fig. 1. Center-periphery behavior of *On* and *Off* receptive fields.

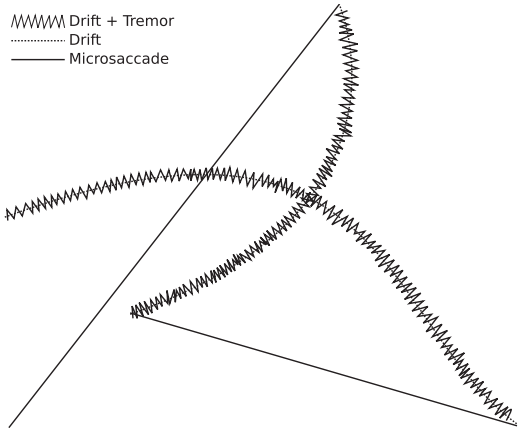

Fig. 2. *Microsaccades*, *drifts* and *tremor* movements. Continuous line shows the fast *microsaccade* movement. Dashed line shows the slow curve of *drifts* movements. Oscillatory line shows the combination of *drifts* and *tremor*.

2.1.3. Microsaccades

Microsaccades are fast eye movements of short duration, about 25 ms [4], displacing the image across a range of several dozens to several hundred photoreceptor widths. The role of *microsaccades* in visual perception have been debated for years. The most accepted idea is that its main role is to prevent fading and thus keep the vision [11,12].

All *microsaccades* are modeled in our retina model as rectilinear movements directed to the center of the visual scene and appearing just after *drifts* with a random angle and amplitude. The amplitude of each *microsaccade* has a mean of 100 μm and a duration of 20 ms. Fig. 2 shows an example of fixational eye movements paths. As can be seen, high-frequency oscillatory paths (*tremor*) are superimposed on *drifts* (curved lines) forming only one path moving slowly. *Microsaccades* (rectilinear lines) appear just after *drifts* and move the image across the retina quickly.

3. Experiments and results

To assess the role and the behavior of *microsaccades* and the other small eye movements in the perception of natural scenes, two experiments have been designed involving different retina models.