Rapid dynamics in the retina

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Abstract

We trained a convolutional neural network (CNN) model on large-scale functional recordings of RGC responses to natural mouse movies, and then used this model to investigate the role of past images in the activity of RGC.

Our work showcases how a combination of experiments with natural stimuli and computational modelling allows discovering ...

1 Introduction

During my internship in Olivier Marre's team at l'Institut de la Vision, I am focusing on computational modeling of the retina. Olivier Marre's team is an interdisciplinary laboratory, hosting four professors and a dozen of interns, Ph.D. students and post-docs, working hand in hand to advance research on the retina. They all have various backgrounds mainly from biology, theoretical physics and engineering. In the context of this project, I've been working closely with Samuele Virgili, a third-year Ph.D. student, whose previous and current projects all focus on the modeling of retinal ganglion cells.

The ability of the visual system to process complex stimuli on different temporal and spatial scales is remarkable. Natural environments are such complex stimuli, and extracting the relevant features at all times is crucial for many species.

Different neurons at different stages of perception are sensitive to specific features of the visual stimulus. From a theoretical point of view, the retina doesn't only play

the role of a receptor for the visual system. It has been proven to be the first layer of feature-sensitive neurons Gollisch and Meister [2010].

Both the accessibility and apparent complexity of the retina makes it a perfect candidate for the study of the front-end of visual processing [Gollisch and Meister, 2010]. In the mouse, the retina is composed of more than 30 parallel feature channels, embodied by ganglion cell types. Through their axons, the optic nerve, they provide information to numerous visual areas in the brain. A few channels are active in the encoding of basic features including luminance changes and motion, that are only combined in more downstream area. Other channels however are known to play a role in the extraction of specific features of natural scene that are relevant to behaviour.

Still, we currently lack an explanation of the features extracted by other channels. One of the historical reasons for this is that synthetic stimuli used to study retinal responses are not complex enough to activate these channels. Hence, they cannot uncover critical response properties encountered in natural environments.

In practice, Karamanlis and colleagues [Kim et al., 2020] have probed a larger complexity in retinal spatial non-linearities thanks to stimuli capturing the statistics of natural environments. As those non-linearities cannot be captured by Linear-Nonlinear (LN) models, convolutional neural networks (CNNs) have become the state-of-the-art approach for predictive modelling of visual processing, not on;y in the retina but also in higher visual areas.

Insight on methods Here, we combined the power of CNN-based modelling with large-scale mutli-electrode recordings from RGCs to investigate the mechanisms of fast adaptation in the retina under natural stimulus conditions. To this end, we recorded RGC responses to flashed images paired together. Each pair is composed of a synthetic adaptation image followed by a natural image. We were able to identify different trend

in the responses of RGCs to natural images, depending on the adaptation image.

To investigate the diversity of this adaptation process and its implementation, we paired deep convolutional models with more traditional modeling. We trained a CNN model on RGC responses to a movie of flashed images. After training, we study how the how this model generalized to images after being adapted with patterns it wasn't trained to. By tweaking part of the model at the inference level, We hope to show that temporal mechanisms such as gain-control play a major role in the fast adaptation of RGCs in a natural context.

2 Background

The retina is part of the central nervous system in vertebrates. It is made of only a handful of layers of neurons. Its first layer is composed of photo-sensitive neurons called photoreceptors, that act as light sensors for the network. They give their excitatory output to bipolar cells, which can be divided into 14 different types and each type responds differently to the same stimulus, allowing for a vast functional diversity. Bipolar cells excite in turn ganglion cells, which finally send the pre-processed visual information to the rest of the brain through the optic nerve. Ganglion cells can also be divided into different functional types (at least 32) and each type is believed to extract a different feature from the visual scene. The retina also has two classes of inhibitory neurons, horizontal and amacrine cells, that further modulate the processing of excitatory cells. Compared to the rest of the brain, its relative simplicity and its relatively easy experimental accessibility make the retina an ideal neural tissue to study using computational models.

Adaptation in the retina To operate optimally in a wide range of stimulation conditions, the retina adapts its responses to the statistics of the visual scene. In particular, it was observed to adapt both to the average luminance (stimulus average) and the average

contrast (stimulus distance from the average or variance).

Visual system can function over a wide range of light intensities, from starlight to a bright sunny day – a luminance range of 10 10 The retinal adaptation to the luminance of the scene is quite simple by nature. For instance, it is known that the retina uses different neuronal pathways at low and high luminance. Rods and their retinal neuronal channels cover the dimmest light while cones facilitate contrast, color and motion discrimination but only in brighter light.

Contrast adaptation, by comparison, is harder to study. It was always studied through the use of simple stimuli. Contrast adaptation is known to have different timescales. While slower contrast adaptation ($\approx 10s$) is better understood, fast adaptation (<1s) is more complex to study. It is still unclear how it affects temporal processing and the sensitivity to stimulus features[Baccus and Meister, 2002]. Furthermore, contrast adaptation can also happen at different scales, either at the whole scene scale (global contrast adaptation) or within one ganglion cell receptive field, the part of the visual field that the cell receives inputs from (local contrast adaptation) [Garvert and Gollisch, 2013]. Local contrast adaptation is especially relevant in understanding how ganglion cells respond to natural images since these stimuli are full of spatial details like edges in which two contrast levels appear simultaneously. Such images are challenging to use, as they can't be summed up to a few statistics easily.

3 Methods

Experimental design. Experimental design is at the border of this work since I don't realize any experiments myself. I will try here to give as few details as necessary for the understanding of the rest of the work. The laboratory has access to three experimental rooms that enable state-of-the-art experimentation on the retina.

Data processing. After an experiments is done, we have to retrieve multi-electrode array experimental data, including semi-automatized spike sorting and cell typing. This process can take up to an entire day for a single experiment. I am also able to share my programming skill to help and improve the data pipeline of the laboratory. This part of my project includes design of experimental stimulus, trustworthy sanity checks and high quality data visualization.

Modeling. This should be the main part of my internship and also the most challenging. We are designing a dynamical model of the retinal fast adaptation. In fact, we mostly look at the evolution of the response from an image to another, meaning that the dynamic we observe only spans two points in time. This reduction makes the model more realistic to study. Most of this job can be summarized as model design, python programming, sensitivity analysis and data fitting. By comparing how different modeling strategies reproduce the observed LSTA in the data, we can gain insight on how fast adaptation to natural scene is implemented in the retina.

Our baseline model is the LNLN model of ganglion cell widely used in the literature. Each neuron is encoded as a spatial linear filter chained with a non-linearity (usually an activation linearity in the like of ReLU). A single layer of subunit neurons, representing bipolar cells, converge into a single modeled ganglion cell. We would like to add temporal dynamics to this model, either by adding a time dimension to the spatial liner filter of the cells or by considering a gain control mechanism. This last mechanism consists in scaling up or down the present output depending on past outputs (Figure TO FIND).

We will first study our models in a data agnostic manner and study its behavior for different set of parameters. We will then fit it on our own experimental data using an efficient optimization framework in python using strategies developed in the field of machine learning.

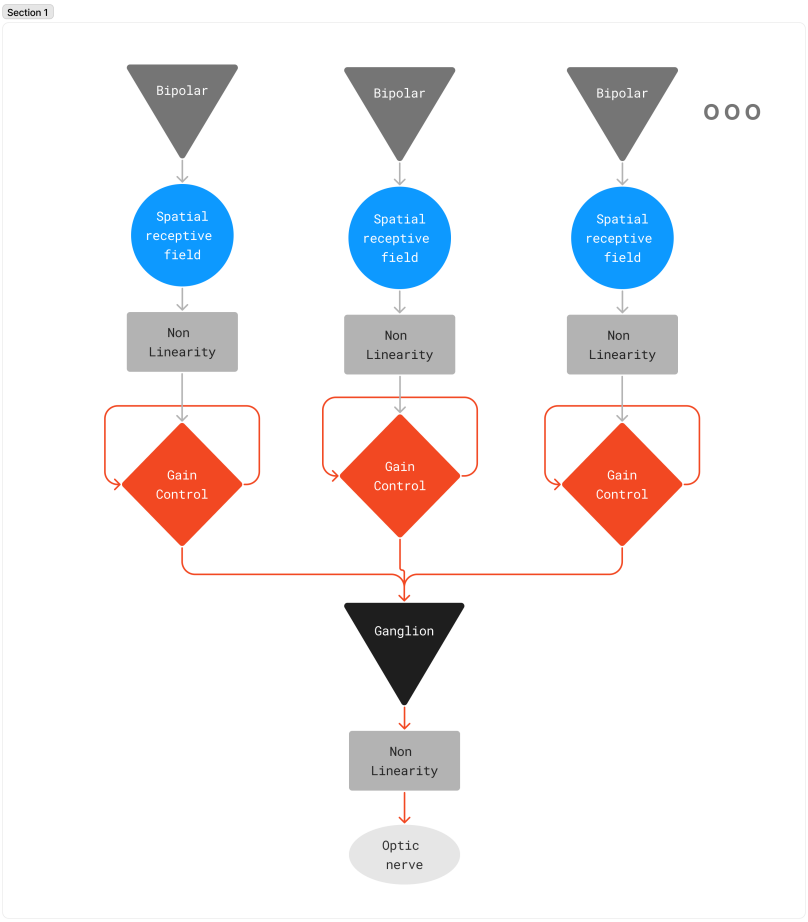

Figure 1: **Quick sketch of a gain control LNLN model.** Each bipolar cell is composed of a linear spatial filter that selectively respond to a part of the scene, a non-linear activation function, and a gain control mechanism that scale its output depending on past events. They all converge into on bipolar cell (forming its own receptive field) of which output is also modeled using a non-linear function.

4 Results

Some idea of speech: *** responses of exemplary RGCs

Here, we investigated fast adaptation in the mouse retina under natural stimulus conditions. To this end, we trained a CNN model on RGC responses to a movie of flashed images appearing naturally in the mouse environment,

5 Conclusion

We combined large-scale recordings of RGC responses to natural movie stimulations with CNN-based modeling to investigate the mechanisms of fast contrast adaptation in the retina.

The modeling of retinal responses to natural stimuli has improved our understanding of complex retinal processing. In a recent review, Karamanlis and colleagues [ADD CITE], suggested three perspectives of study on the retinal encoding of natural scenes: The circuit perspective ('How is the retinal code implemented?'), the normative perspective ('Why is it complimented this way?) and the coding perspective ('What is the code used by the retina?'). In this work, We focus on the 'what'. By exploring the response of the retina to a portion of the spatio-temporal stimuli space we can gain insight into the code used by the retina on that subspace. To explore further the 'how' perspective, one would need to study how the different known types of cells in the retina participate in that encoding. This poses the challenge of bridging the typing of cells from functional and anatomical perspectives. The normative perspective has also been explored using deep CNNs with anatomically realistic constrained. It is likely that species with simpler cortical circuitry, as mice, have a stronger need for upstream feature extraction, in the retina. In opposition, species with computationally powerful cortexes such as primates

can deal with more faithful and linear representations of the visual inputs. Some studies admirably developed approaches that allow investigation of retinal processing from all three perspectives [ADD CITE].

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Supplementary materials