Eye Movements and The Visual System: An Insight From Trans-Saccadic Adaptation

Yann Longpré

Master of Science

IPN

McGill University

Montréal

April 2020

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Science in the Integrated Program in Neuroscience

DEDICATION

This document is dedicated to all the animals that contribute to science.

ACKNOWLEDGEMENTS

Special thanks to Julie Coursol and Cathy Hunt for outstanding animal care and Dr. Fernando Churaund for help with surgeries. I am grateful for the support of Dr. Chris Pack, the assistance of Naomi Takeda, the technical advice from Dr. Pedro Vieira and the collaboration with Pooya Laamerad and Yavar Korkian. Thanks to Dr. Matt Krause for his insights throughout my research and for commenting on my manuscript. Un grand merci à Sophie Aublet et Yoelvis González Pérez pour les nombreuses relectures et pour les longs débats et corrections. Ce document n'aurait pas été possible sans l'appui de Taís Grote, qui m'a épaulé tout au long de mes études.

CONTRIBUTIONS OF THE AUTHORS

I, Yann Longpré, designed the experiment in collaboration with Dr. Chris Pack. Then, Y.L. performed the experiment, analyzed the data and wrote the thesis under the supervision of C.P.

ABSTRACT

Primates, who use vision as their primary tool for navigating the environment, constantly move their eyes, making short fixations punctuated by abrupt saccades. With each fixation, the neurons of the visual system adapt locally to the current statistical properties of the stimulus to maximize the assimilation of information. When a saccade moves the retina, the visual system (retinotopic) must suddenly encode a different portion of the image. In this thesis, I seek to verify whether the influence of adaptation is maintained trans-saccadically. To do this, I performed electrophysiological recordings of cortical neurons of the area V4 of awake macaques doing a simple visually guided oculomotor task. The effect of the saccade on the dynamics of adaptation is isolated by using a simulated saccade paradigm. The outcome of my experiments is that adaptation has a profound influence on visual processing at the neuronal level, decreasing the amplitude of the response in a time-scale relevant to natural behavior. When there is an eye movement between the adapter and the probe, the impact of the adaptation greatly decreases. However, the benefits of the saccade are temporary, as the delayed post-saccadic probes are impacted by the adapter again. Visualization of the dynamics of neuronal populations using a state-space analysis illustrates how the trajectories leading to the stimulus can influence the neural response. My interpretation of the data is that the saccade momentarily places the visual system in a state conducive to an impartial response.

ABRÉGÉ

Les primates, qui utilisent la vision comme outil principal pour naviguer l'environnement, remuent les yeux constamment, faisant de courtes fixations ponctuées d'abruptes saccades. À chaque fixation, les neurones du système visuel s'adaptent localement aux propriétés actuelles du stimulus pour maximiser l'assimilation d'information. Lorsque la saccade déplace la rétine, le système visuel (rétinotopique) doit soudainement encoder une différente partie de l'image. Dans cette dissertation, je cherche à vérifier si l'influence de l'adaptation est maintenue trans-saccadiquement. Pour ce faire, j'ai procédé à l'enregistrement électrophysiologique de neurones corticaux de la région V4 de macaques éveillés performant une simple tâche oculomotrice guidée visuellement. L'utilisation d'un paradigme de saccades simulées permet d'isoler l'effet de la saccade sur les dynamiques de l'adaptation. Le bilan de mes expérimentations est le suivant : l'adaptation a une profonde influence sur la réponse visuelle en ayant pour effet d'en réduire l'amplitude dans une échelle de temps propre au comportement naturel. Cependant, lorsqu'il y a un mouvement oculaire entre l'adaptateur et la sonde, les répercutions de l'adaptation diminuent grandement. Néanmoins, les bienfaits de la saccade ne sont que temporaires, alors que les sondes post-saccadiques prorogées subissent à nouveau les répercussions de l'adaptateur. La visualisation des dynamiques de populations neuronales par une analyse d'état spatial illustre comment les trajectoires menant au stimulus peuvent influencer la réponse neuronale. En outre, mon interprétation des données recueillies est que la saccade place momentanément le système visuel dans un état propice à une réponse impartiale.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1
Introduction

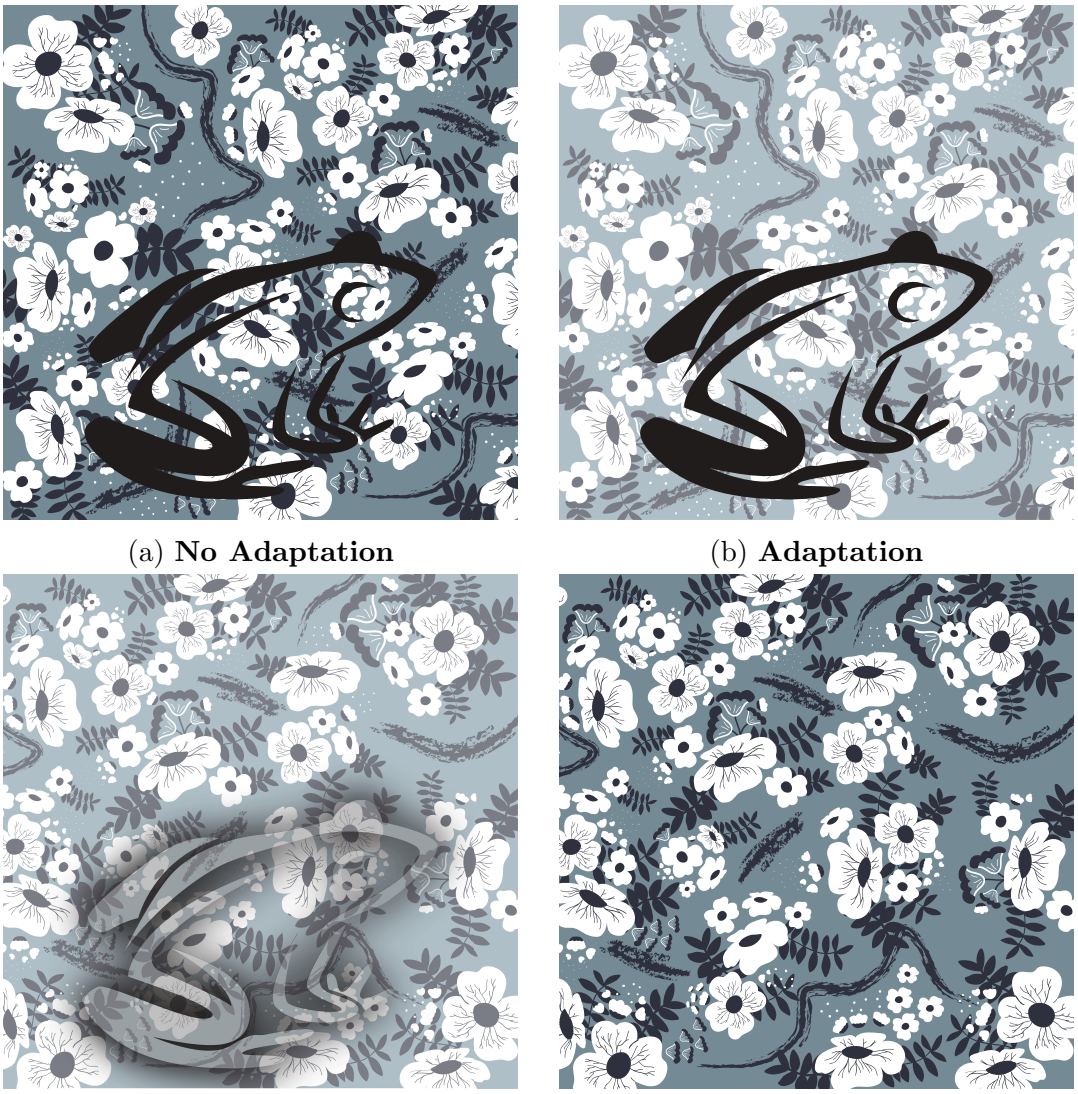
1.1 Introduction

This thesis focuses on the fascinating perceptual capacity of the visual system of primates. Humans and monkeys use their eyes as the primary sensory organ to probe the world and navigate the environment. Since natural scenes contain an overabundance of data, deciphering the visual space requires considerably sensitive measurements. The problem is solved by a specialized structure called the fovea, which dominates our visual perception and allows for our rich and colourful visual experience. The small dimple in the retina contains a high density of cone photoreceptors (Rochon-Duvigneaud, 1907). However, this acutely sensitive region only covers about 1 degree of the visual field. Thus, an optimal sampling strategy involves rapid eye movements, called saccades, which bring objects of interest near the fovea. The saccade is the dominant visual search behavior. To scan the environment, we must make several saccades every second. There are stringent time constraints on perception in a real-world task. When a macaque is swinging in the branches, the visual system can only spare a couple of hundred milliseconds to decipher the information on each fixation. The visual system faces the complicated problem of reconstructing the scene from a stream of discrete epochs of fixations. Given that each fixation is incomplete, the brain must integrate information across saccades to form a continuous visual percept.

The goal of the visual system is sight, the ability to detect and interpret the surrounding environment using light. To do so, the visual system turns light into patterns of neuronal activity. This process begins with photoreceptors in the retina, which transduces the vicinal quantity (luminance) and wavelength (color) of photons into a nervous signal. From there, information cascades in parallel hierarchies forming a series of retinotopic maps in the visual cortex. Each neuron of the striate and extrastriate cortices processes a spatially restricted portion of the retinal input.

Natural scene images pose a considerable challenge, as they have a substantial spatial variation. Yet, locally, images hold a lot of uninformative redundancy. To optimize sensory encoding, neurons constantly adjust to local statistical properties, an ability called adaptation. The nervous system adjusts to the environment over a very wide range of timescales (Patterson et al., 2013). In this thesis, I am interested in the rapid readjustments that occur within the time frame of natural fixations. Short-term adaptation is related to instantaneous gain control and normalization mechanisms. It serves to enhance information transmission (Sharpee et al., 2006) by reducing the local redundancy (Wainwright et al., 2002) (see figure 1–1b for illustration).

The problem arises in natural tasks, as there is little correlation in the local image properties between successive fixations (Frazor and Geisler, 2006). Consequently, when a saccade scrambles the input to the visual system, adaptation to the previous stimulus is no longer favourable. The problem arises from the fact that the time course of adaptation (Albrecht et al., 2003) is too sluggish compared to the short duration of the eye movement. Scrutinized jointly, these considerations imply that



(a) **No Adaptation** (b) **Adaptation**

(c) **Aftereffect** (d) **Saccadic Release**

Figure 1–1: A visual scene contains an overabundance of information (a). Adaptation serves to enhance information transmission by reducing the local redundancy (b). The saccade shifts the cortical input, adaptation to the pre-saccadic is no longer relevant. In fact, the adaptation aftereffect (c) would be detrimental. My proposition is that each fixation could begin in a neutral state (d).

an active interaction between the oculomotor system and the visual system would be beneficial.

The goal of my research is to elucidate the role of ocular motion in modulating the response of visual neurons. I wonder what the consequence of a saccade on adaptation is. In short, I want to know if the retinal trace of adaptation lingers after an eye movement, or if each fixation starts anew.

To answer this question, I performed single-unit neuronal recordings from awake macaques performing an oculomotor task. The data I present here shows empirical evidence of an active release from the effect of a pre-saccadic adaptation immediately following an eye movement. However, further analysis reveals that the aftereffect of adaptation is not simply erased from the neuronal population. Rather, it shows that the impact of a saccade on adaptation is transient.

1.2 Background Information

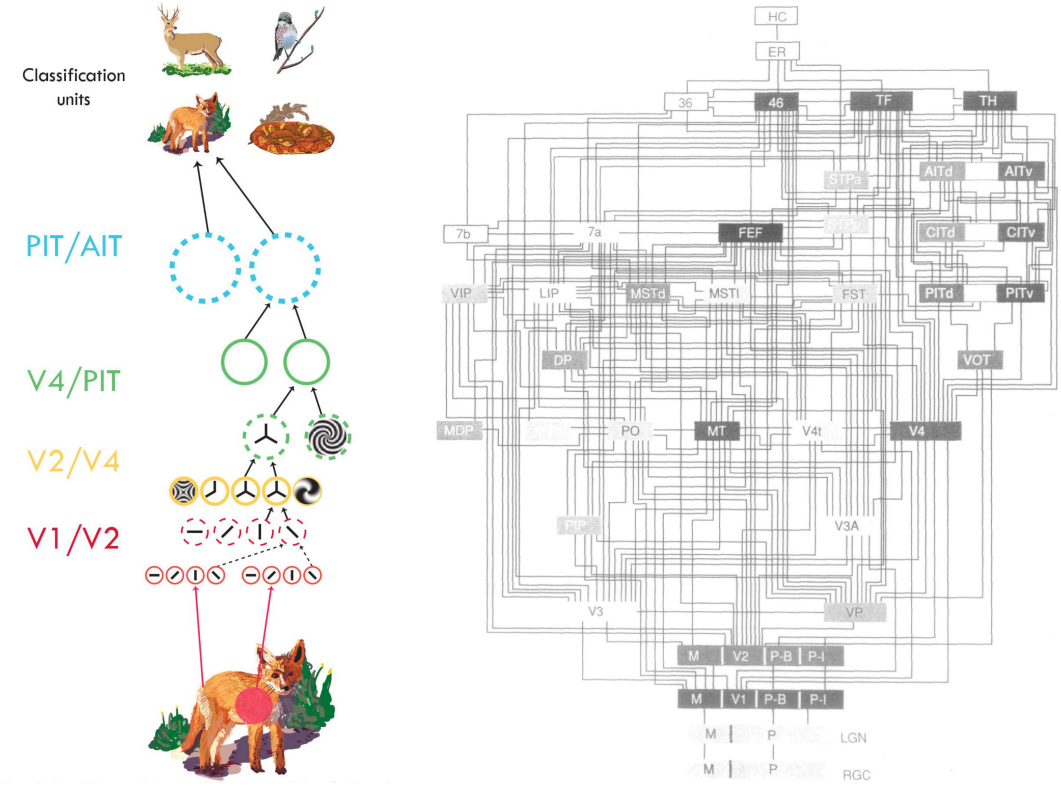
1.2.1 Hierarchical Model of Perception

To fathom perception, we must understand how sensory information is transformed in the cortex. The first neuronal filter of the visual system is through the retinal ganglion cells, which are wired to photoreceptor cells in such a way to compute the difference in luminance between the center and the surrounding (Hubel and Wiesel, 1960). A neuronal signal from retinal ganglion cells is carried through the lateral geniculate nucleus (LGN) of the thalamus to the primary visual cortex. The pioneering research of Hubel and Wiesel (Hubel and Wiesel, 1962) have modelled the response of V1 neuron in a hierarchical network. For example, a simple cell, which responds to bar stimuli, assembles the output of several spatiotopically organized LGN

cells. At the next stage, a complex cell selectively pools simple cells to construct a location-invariant representation of the stimulus. Contemporary models suggest that tuning to complex stimuli arises from combining simple units in successive processing layers (Riesenhuber and Poggio, 1999).

Complexity arises from consecutive actions of repeated simple computational modules. The brain has a modular design that relies on a set of canonical operations applied across modalities (Carandini and Heeger, 2012). The visual cortex functions through a series of hierarchical filters, which transforms the sensory input into increasingly intricate representations. For instance, area V4 is part of the ventral visual stream, which is illustrated in figure 1–2a. The core of object recognition is solved by the extrastriate area V2 and V4 and the inferotemporal (IT) cortex (DiCarlo et al., 2012). As we move up the visual hierarchy, we get an increase in the level of abstraction of the representation. Lower-level areas have smaller receptive fields and are tuned to simple sensory structures. But information is gradually untangled as the brain progressively realizes an object representation that is tolerant to identity-preserving transformations (DiCarlo and Cox, 2007). Importantly, at the level of area V4, where I recorded, neurons have receptive fields that are spatially localized and retinotopic.

The paradigm of vision research owes a lot to the seminal work of David Marr (Marr, 1982), which lays the philosophical groundwork to the investigation of the visual system as an information-processing system. It is important, as a researcher, to be aware of the tacit assumptions underlying the archetypal view. In particular, there is the presumption of the pipeline nature of information processing (Stevens,



(a) **Ventral hierarchy** (b) **Interleaved connectivity**

Figure 1–2: Sketch of the ventral visual stream hierarchy (a (Serre, 2013)). Representations arise from multiple processing stages tuned to increasingly complex features of the stimulus. In reality, the visual cortex is composed of many interleaved hierarchies emanating from the magnocellular and parvocellular streams from the retina (b (Felleman and Van, 1991)). The majority of these connections have been demonstrated to be reciprocal pathways.

2012), which is that we expect a directional flow of information from earlier to later areas. In contradistinction, there are substantial reciprocal connections and bidirectional concurrent flow of information throughout the visual system (Felleman and Van, 1991).

Strictly feed-forward models have provided fruitfully, with resounding success in understanding the filters implemented by lower visual areas. Further, deep convolutional neural networks (LeCun et al., 1998) have achieved impressive performance (Krizhevsky et al., 2012), showing that these models can sufficiently implement object recognition. Yet, they lack the raw generalization power of biological systems. To understand the brain entirely, we have to consider the role of the complex bidirectional architecture (Hochstein and Ahissar, 2002) and the alternative pathway for visual information through the cortico-thalamo-cortical (CTC) recurrent connections between the extrastriate cortex and the pulvinar nuclei of the thalamus (Sherman and Guillery, 2006) (see figure 1–4a).

A biological model of the ventral visual pathway (O'Reilly et al., 2013) can benefit from the inclusion of a recurrent architecture. Top-down connections can contribute to the brain's robustness to degradations, as in partial occlusion. While bottom-up connections represent sensory features, top-down connections can reflect semantic information (see figure 1–3). In this model, the brain can resolve ambiguities of the input by reinforcing probable interpretations about the underlying stimulus.

The anatomical hierarchy should be taken as an idealization, and it does not reveal the whole potential of the brain (Hegde and Felleman, 2007). Although it

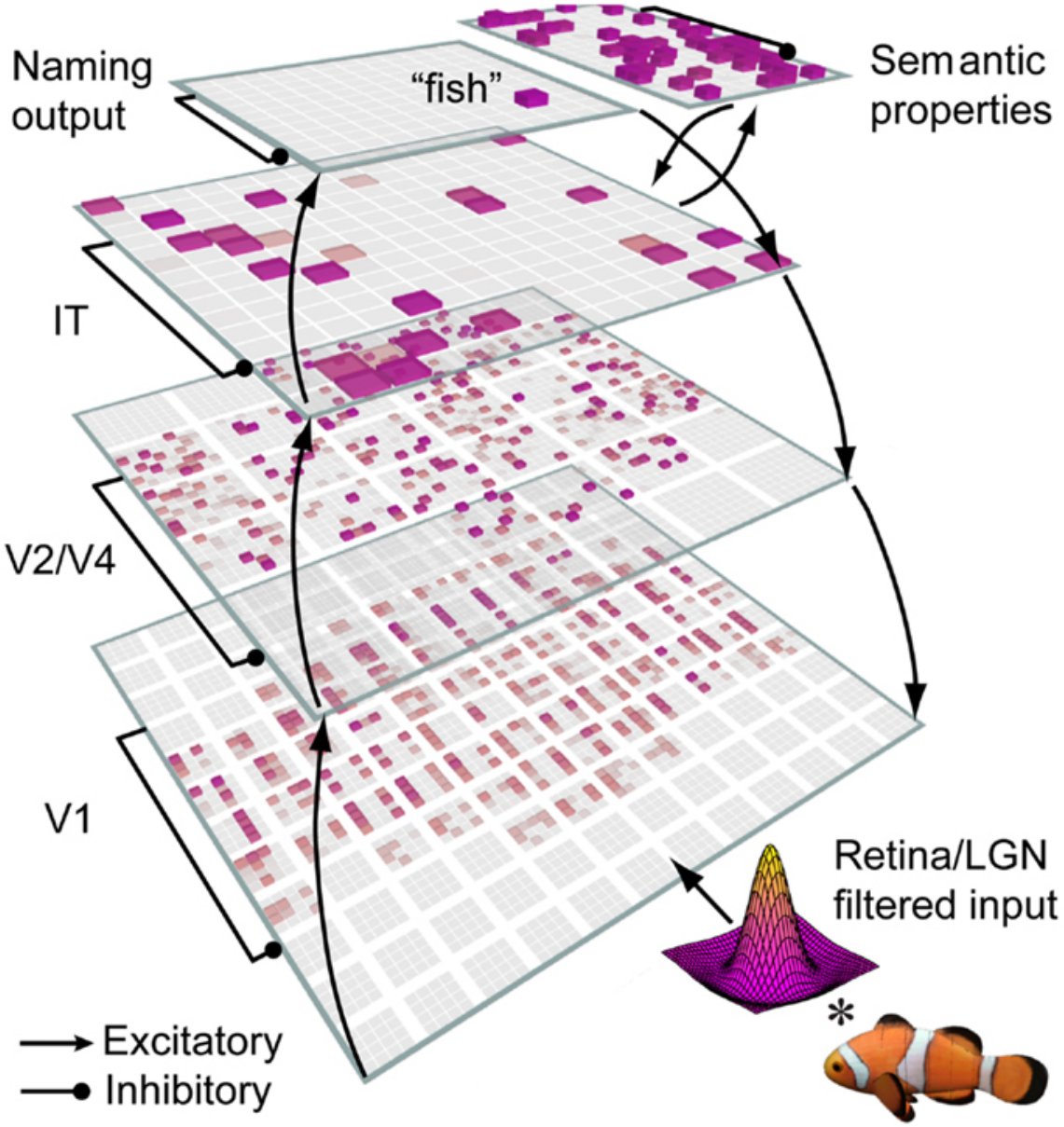


Figure 1–3: **Recurrent Hierarchy.** Taken from (O'Reilly et al., 2013). Bottom-up connections represent sensory features, while top-down connections can reflect semantic information. In addition to the large scale inter-cortical recurrent connections, there are also local inhibitory connections. Adaptation, or normalization is implemented in these horizontal connections at every level (Carandini and Heeger, 2012).

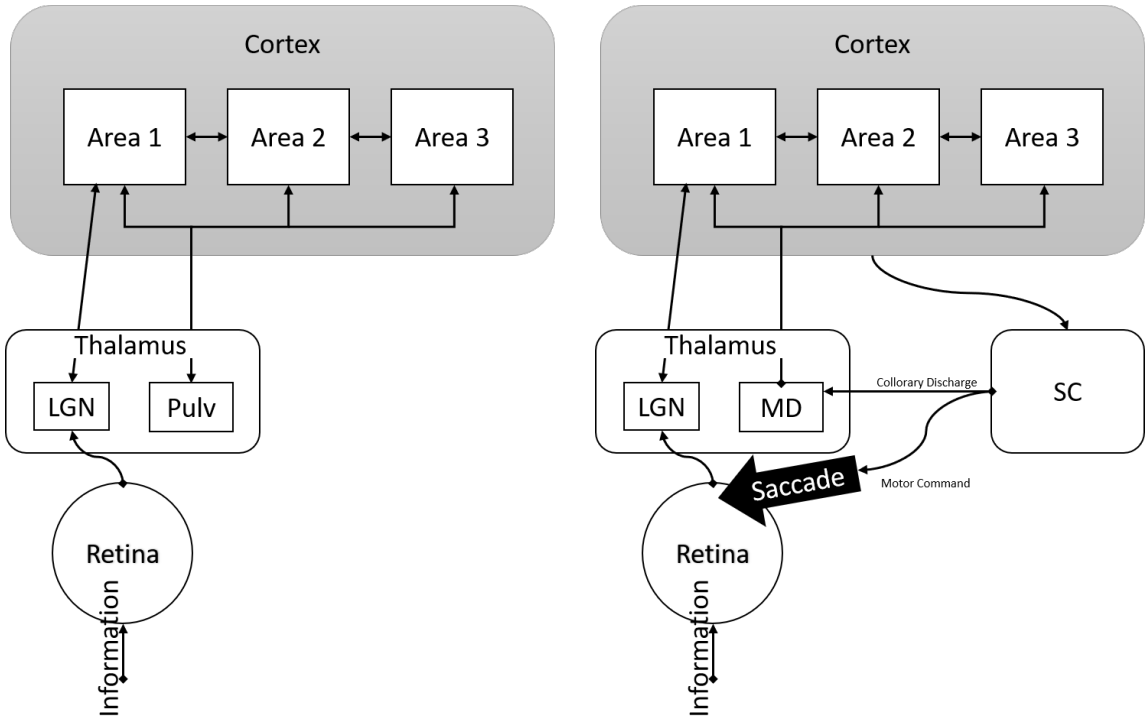
holds that representation become increasingly complex at the population level, individual neurons in each area have a broad distribution of tuning and receptive field characteristics (Serre, 2013).

Finding a biological correlate to the hierarchical model is not a given. For example, the interareal comparison of shape representation patterns between V2 and V4 reveals that functional differences between areas do not parallel the stepwise hierarchical organization (Hegdé and Van Essen, 2007). A more accurate picture of the visual cortex is that it is composed of multiple parallel processing streams (figure 1–2b). Cortical areas are organized in interleaved retinotopic maps composed of neuronal columns specialized in different feature dimensions of the stimulus.

1.2.2 Adaptation

Perception cannot occur without a context, the information encoded in the response of neurons is dependent on the sensory history. And, because a natural scene contains a wide dynamic range, real-time sensory processing requires rapid readjustments. The perceptual mechanism called adaptation is a short-term experience-dependent plasticity, which has sparked a rich history of research (Kohn, 2007).

Adaptation is ubiquitous throughout all sensory modalities and hierarchical levels (Wark et al., 2007). It is present at virtually every time scales, from milliseconds to millennia, and it likely involves multiple mechanisms. Adaptation can be implemented locally in single neurons, either from intrinsic cellular properties (Whitmire and Stanley, 2016) or plastic changes of the synaptic kinetic (Abbott et al., 1997). Beyond that, it can arise from the recurrent network dynamics of a population of neurons (del Mar Quiroga et al., 2016). Adaptation instantiates an efficient coding



(a) **Recurrent cortical connections through the pulvinar nucleus**

(b) **Efferent motor copy from the superior colliculus**

Figure 1–4: Basic hierarchical models of the visual system assume a linear flow of information across the lateral geniculate nucleus (LGN) of the thalamus and cascading from early to later areas in the cortex. In truth, there are significant recurrent connections through the cortico-thalamo-cortical pathway via the pulvinar nucleus (pulv) (a, inspired by (Hegde and Felleman, 2007)). Gaze movement control is initiated by a midbrain sensorimotor structure called the superior colliculus (SC). It provides a motor command to the oculomotor nuclei of the brainstem reticular formation while an efferent copy of the motor signal is carried in ascending pathways through the medial dorsal (MD) nucleus of the thalamus (b).

strategy (Barlow, 1990) for neurons who constantly adjust to match local stimulus statistics. It is a fundamental component of sensory information processing, which helps the visual system to achieve constancy of perception.

In this project, the form of adaptation studied is the contrast adaptation. The presentation of a high contrast masking stimulus leads to reduced neuronal responsiveness to a subsequent test stimulus (Sclar et al., 1989). Experimentally, the contrast response function (CRF) of a neuron is evaluated by tracking its response to different stimulus contrast levels. The consequences of adaptation are illustrated in systematic changes in the CRF. The reduced neuronal responsiveness can manifest in two ways (see figure 1–5), either a downward shift (response gain) or a rightward shift (contrast gain) of the CRF (Cavanaugh et al., 2002). The first implicates a reduction in the response amplitude, which functions through an output scaling whose purpose may be to avoid neuronal fatigue (Vinken et al., 2019). The second relates to an attenuation of the contrast sensitivity. Via an input scaling, there is a readjustment of the sensitivity center of a neuron dynamic range toward the recent stimulus statistics.

1.2.3 Saccade

Saccadic eye movements are a prevalent part of our visual search behavior, and yet they leave little conscious traces. This paradox has fueled a lot of research on the question of visual continuity (Wurtz, 2008), and it was uncovered that the processing of a visual stimulus is modulated by a corollary discharge emanating from the oculomotor system (Sommer and Wurtz, 2008) (see diagram on figure 1–4b). To be clear, saccades impose a strong constraint on the visual system, and the brain must

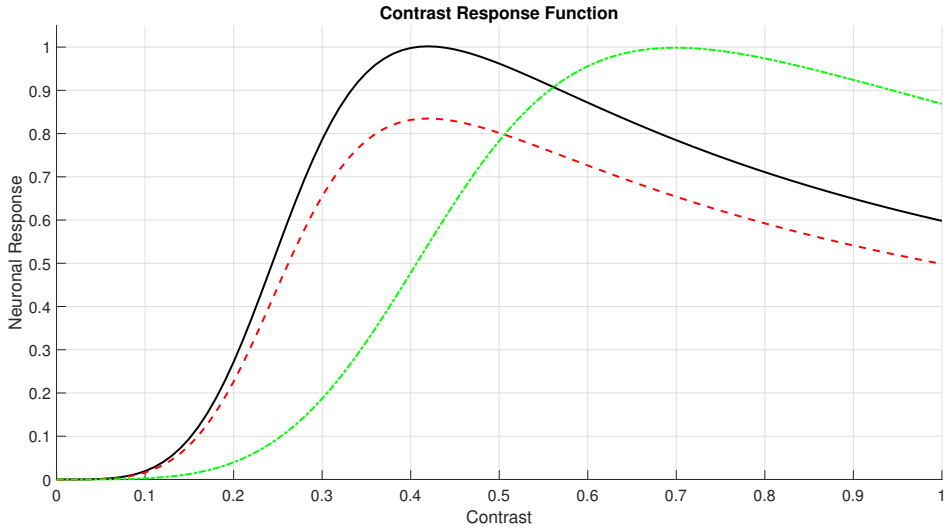


Figure 1–5: **Example CRF for typical V4 neurons** (solid black line). The effect of adaptation can manifest as a downward shift (red dashed line) or a rightward shift (green dashed line). These represent modulations of the neuronal response amplitude and contrast sensitivity, respectively.

have active mechanisms to avoid perceptual disturbances (Ibbotson and Krekelberg, 2011).

There are several physiological events associated with visually guided saccades. For example, there is saccadic suppression (Matin et al., 1972; Diamond et al., 2000), which functionally may be responsible for masking the perceptual trace left by eye movements (Campbell and Wurtz, 1978). In particular, an electrophysiological study (Zanos et al., 2016) in macaque V4 shows a strong suppression of the neuronal firing rate both pre and perisaccadic, as well as an increase in α LFP power. This effect could be interpreted as a form of active inattention.

The inhibition during eye movements is followed by an enhancement of neuronal sensitivity post-saccadically (Ibbotson et al., 2007), forming a biphasic modulation

of the neuronal activity. These effects are widespread and influence the activity of both main visual pathways (Reppas et al., 2002), although the respective influence and timing of both components vary for different brain areas. This could reflect differences in experimental paradigms, or, more likely, it shows that the saccadic modulations have multiple implementations throughout the cortex and are not simply inherited from lower-level areas.

Another interesting phenomenon that occurs with saccade is called remapping (JR Duhamel and Goldberg, 1992), which is a transient shift in the neuron receptive field location that anticipates the post-saccadic state. There are several different phenomena that have shared the moniker: forward remapping, backward remapping, convergent remapping. There is no established agreement within the scientific community on the modalities of remapping, and it seems that there are several mechanisms at play (Neupane et al., 2016). Further, there are important links between remapping and attention (Cavanagh et al., 2010). In all, different versions of remapping share a common characteristic: the neuronal response becomes more fluid around the time of the saccade.

Most studies involving saccades have focused on the question of continuity. Comparatively, little work has been done to address the complementary question regarding the discrete nature of each fixation percept. The brain receives a continuous stream of information that must be segmented and analyzed into a distinct snapshot for each fixation.

Some psychophysical evidence using bistable stimuli shows that saccades eradicate past perceptual states of ambiguous figures (Ross and Ma-Wyatt, 2004). Another experiment using real and simulated saccades has shown that the magnitude of the influence of the preceding stimulus is significantly reduced by an eye movement (Paradiso et al., 2012). The authors suggest that the saccade plays an important role in resetting perception for each fixation. Also, eye movements can increase the ability of the visual system to segregate trans-saccadic stimuli as separate perceptual objects (De Pisapia et al., 2010).

An investigation, specifically engaging the effect of contrast adaptation on the processing of the post-saccadic stimuli in V1 neurons, Guez (2015) reported that there was no complete reset from the previous fixation. Nevertheless, their results revealed an increase in the operating range and improved discriminability between contrasts following an eye movement. Conversely, Gawne and Woods (2003) found no evidence for a saccadic reset. Instead, they have shown that responses of V1 neurons are strongly modulated by the scene that occurred before the saccade, such that neurons could encode the differences across saccades.

1.3 Rationale

In this thesis, I seek to elucidate if there is an interaction between adaptation and eye movements: do the effects of adaptation persist across saccades? This would certainly be the case in the absence of an active modulation since the aftereffect of adaptation lasts longer than the duration of a saccade (see figure 1–1). Given that there is little correlation in the image statistics between successive fixations (Frazor and Geisler, 2006), the optimal processing strategy should involve resetting

adaptation with each fixation. I propose that ocular motion has an impact on visual processing, which should manifest in a diminution of the aftereffect of adaptation trans-saccadically.

To test the hypothesis, I used a simulated saccade paradigm (Paradiso et al., 2012). I leveraged the retinotopic organization of the visual system to devise two conditions which have identical visual stimulations at the retina and only differ by the presence of an eye movement. By matching the timing of the input to the visual system, I can control for the effect of the oculomotor motion on the neuronal response following adaptation. I investigated the response of individual neurons to a flashed test stimulus of varying contrasts following adaptation to a strong adapter stimulus. To do so, I modelled the contrast response and parametrized the gain and sensitivity change caused by adaptation, which is compared with or without eye movements across the population of neurons.

Because of the emergent properties of complex systems, it stands to reason that investigating the response of individual neurons is not the same as contemplating the activity of the population as a whole. In chapter 4, I used a state-space analysis in an effort to illustrate at the high dimension dynamics at play. The visualization of neuronal trajectory led me to refine my interpretation of the situation. Instead of saying that the saccade releases the effect of adaptation, I suggest that the saccade actively drives the neuronal manifold toward a state that is propitious to the optimal processing of the subsequent stimulus. Although the distinction might appear only semantic, it is nevertheless noteworthy. Adaptation represents a form of short-term

memory and simply erasing the previous state might not be the most advantageous option. Instead, a saccade opens a favorable window for the incoming stimulus.

I gathered data in a different condition that allowed me to make a testable hypothesis regarding this distinction. In some experiment sessions, there was a delay in the presentation of the post-saccadic stimulus. If the first interpretation is correct and saccades erase the pre-saccadic adaptation, there should be a similar release from adaptation in the delayed sessions, or an improved result given the extra time to recover. In contrary, if the second explanation is valid, we might observe no modulation from the saccade, as the stimulus is presented outside of the opportune frame. Both alternatives are presented empirically in chapter 3, and discussed in chapter 5

CHAPTER 2
General Methodology

2.1 Electrophysiological Recordings

In order to answer my questions, in gathered data from neurons of the extrastriate visual area V4 of macaques. Two animals were involved in the research. The first, monkey P, was equipped with a chronic 10 x 10 microelectrode array (Utah Array; Blackrock Microsystem) over a peripheral portion of the dorsal V4, which is conveniently positioned on the surface of the cortex (described previously: (Neupane et al., 2017; Zanos et al., 2016)). The second, monkey A was instead implanted with a more flexible recording cylinder, and 32 channels linear electrodes (V-probe; Plexon) were used to acquire neuronal signals. Because of the anatomical position of dorsal V4, its proximity to the ear, it was infeasible to implement the recording chamber to access the same region as Monkey P without compromising the animal health. Instead, it was elected to center the chamber above the ventral portion of area V4 (figure 2–1). Given the diameter of the recording cylinder (20 mm), this placement allows access to ventral V4 as well as the neighbouring region of V3 (posterior) and TEO (anterior). All aspects of the experiments were approved by the Animal Care Committee of the Montreal Neurological Institute and were conducted in compliance with regulations established by the Canadian Council of Animal Care.

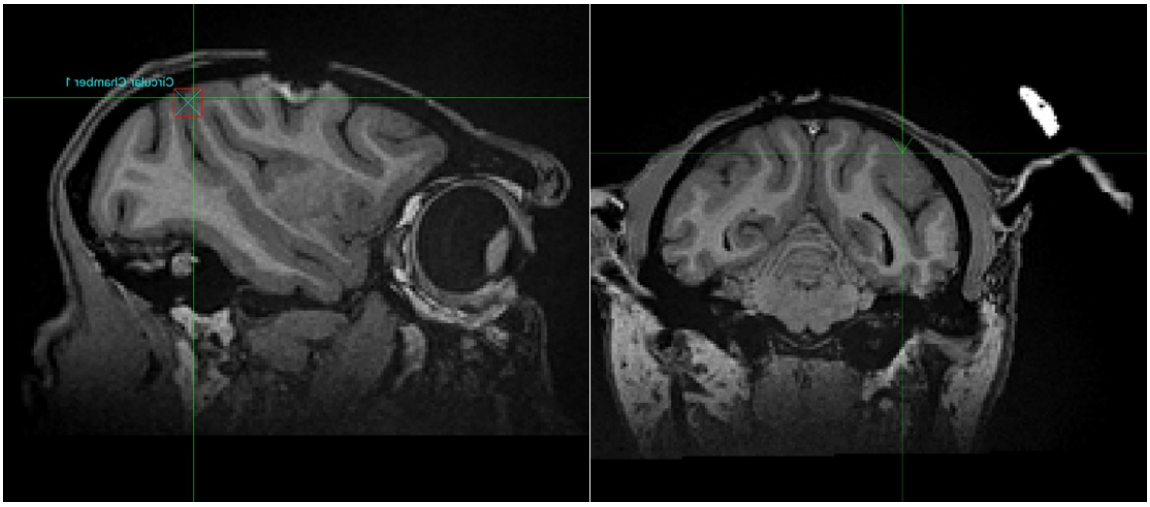


Figure 2–1: **Sagittal and coronal brain scans from monkey A.** The green vertical line represents the surgical target for the center of the recording chamber. Ventral Area V4 is in the middle third of the occipital temporal sulcus, with peripheral representations medially.

2.2 Behavior

The behavioral component of the experiment was the same throughout. The monkey were instructed to make guided saccades between visual targets presented on the screen. The experimentation were coordinated using a MatLab extension called MonkeyLogic (Asaad et al., 2012).

Eye Tracking. The eye position was monitored at 1,000 Hz using an infrared eye tracker (Eyelink; SR Research). The saccade onset was determined as the time when the eye position left the first fixation and crossed a horizontal location corresponding to two-thirds of the saccade. The stimulus was presented at the saccade offset when the fixation was stable in the second fixation spot. I removed any outlier saccades with a duration exceeding 55 ms, more uncommon with monkey P (0.3%)

than monkey A (3%). As seen in figure 2–2, the duration of eye movements was consistent, with the acquisition of the stable fixation contributing most of the variance. Monkey P had performed saccade tasks for several years and his behavior was almost machinelike, with very little irregularities. In contrast, monkey A was agnostic to the task before training, which became apparent in imprecise saccades leading to a variability of the stimulus presentation. Nonetheless, the experiment was biased in favor of the control since the average duration of the recovery period was longer for simulated saccades (45 ms) than real saccades (Monkey P $\mu = 30\,ms$, Monkey A $\mu = 40\,ms$), meaning that positive results cannot be attributed to timing difference between the experimental conditions.

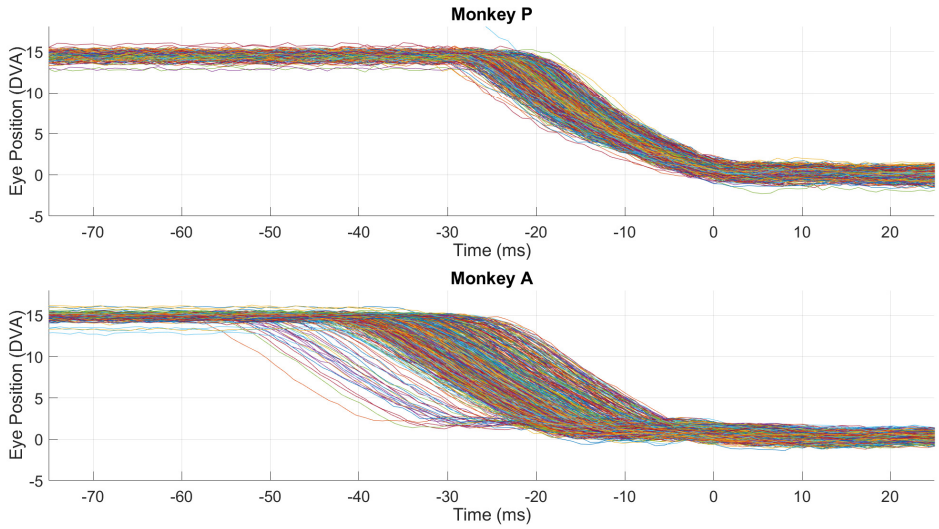


Figure 2–2: **Saccadic eye traces for both monkeys.** Time zero represents the probe stimulus presentation. Monkey P exhibits a very stereotypical behavior while monkey A is more inconsistent in her eye movements, leading to more variability in the stimulus timing. Most variance in the saccade duration is due to a delay in acquiring the second fixation on imprecise saccades.

2.3 Receptive Field Mapping

Automatic receptive field mapping was performed via a rudimentary reverse correlation algorithm by taking the averaged firing rate elicited by flashed probe stimuli randomly presented from a grid covering the expected receptive field locations, as in (Neupane et al., 2016; Zirnsak et al., 2014). In the case of monkey P, the receptive field location was stable over time, with regular receptive fields in the contralateral lower quadrant, peripheral at about 10 degrees from fixation. In reverse, receptive fields in monkey A were heterogeneous. Given the depth of the penetration (about 20 to 30 millimeters, from the top of the brain, see figure 2–1), and the soft complexion of the brain, there was a lot of variance in the final recording location. In addition, area V4 is not a homogeneous functional area (Roe et al., 2012). Rather, area V4 is composed of different interleaved modules (Tanigawa et al., 2010) tuned to many simple or complex modalities like orientation, color and even motion (Li et al., 2013). Accordingly, it was necessary to do a manual receptive field routine daily to get a sense of the current neuronal properties. For neurons that were sensitive to simple stimuli, I also ran the automatic mapping to verify the manual result. As expected (Gattass et al., 1988), I found receptive field locations from the vertical meridian, the posterior boundary with V3, to the horizontal meridian, the anterior boundary with TEO; all in the upper contralateral visual field. I tried to focus my recordings on neurons that were squarely in the quadrant as opposed to the meridians, as those correspond to the transitional areas (Boussaoud et al., 1991). One thing that stood out was the omnipresence of foveal and parafoveal locations. In many cases, the fixation target itself was a strong stimulus for the neurons. I was forced to discard

these neurons from my analysis as the experimental design cannot handle such competing stimuli gracefully. This highlights a weakness of the classical paradigm of vision science (fixation - stimulus presentation), which mostly ignores what happens at the most prominent location, the fovea.

Significant Unit Selection. Next, I isolated the neurons that had a meaningful response by comparing the response between the adapter stimulus and the baseline activity during fixation. To do so, I applied a two-sample Kolmogorov-Smirnov test (Massey Jr, 1951) which tests against the null hypothesis that the two samples are drawn from the same distribution. I tested systematically at intervals of 25 ms for 250 ms after the presentation of the adapter stimulus and classified the neuron as responsive if the test rejected the null hypothesis at a significance level of $\alpha = 0.05$. Then, I proceeded with a quick visual inspection of the peristimulus time histogram (PSTH) to verify the algorithmic selection (for example, see figure 2–3).

2.4 Experimental Delay

In order to sample the heterogenous V4 neurons sourced from single unit recordings in monkey A, I had to use the updated MonkeyLogic runtime V2, which allowed for more flexibility in dynamic stimulus presentation. However, a malfunction appeared after a reasonable amount of data was gathered: there was a delay in the post-saccadic stimulus presentation. I had to revert to the simpler software implementation to get temporal precision in the behavioral control. Essentially, it was the complexity of the program that became its casualty. Perhaps this is a common theme in research, a sort of uncertainty principle of neuroscience. Ultimately, this

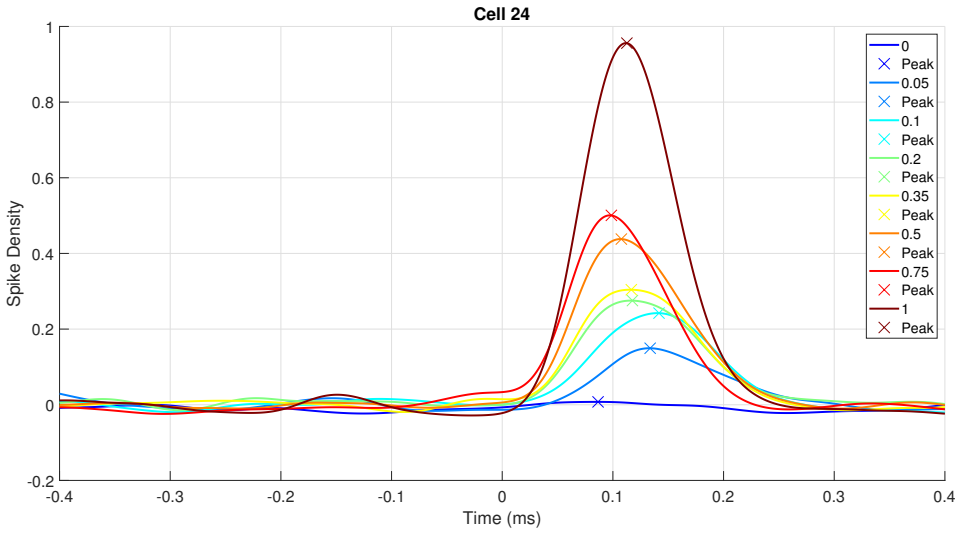


Figure 2–3: **Averaged PSTH for an example neuron at varying levels of contrasts.** This is a typical neuronal profile to the probe stimulus, without a saccade or an adapter. Time zero coincide with the probe stimulus presentation. The x represents the peak for each contrast, which is used trial-by-trial to fit the contrast response function.

mishap created a separate dataset, thus allowing me to specify my hypothesis and further my understanding of the effect of the saccade on the visual system.

.

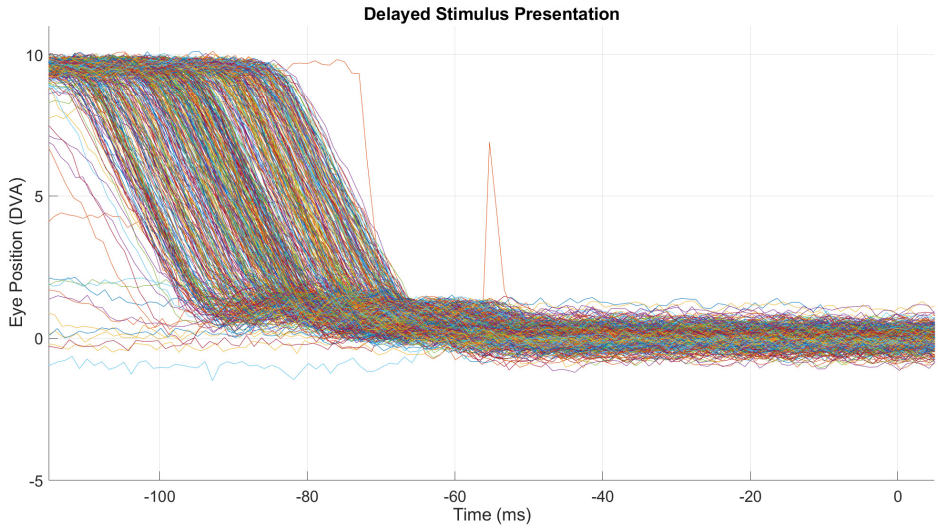


Figure 2–4: **Saccadic eye traces for delayed experiment in monkey A.** In experimental session ran using version V2 of MonkeyLogic, there is a delay in the probe presentation after the saccade. The saccade offset was suppose to correspond to the probe presentation (time zero), but in this case, there is a delay of about 100ms post-saccadically before the probe stimulus presentation.

CHAPTER 3
The Experiment

3.1 Introduction

Primates use their visual system as a primary means to gather information and navigate the environment. In a natural setting, visual stimuli habitually come into focus via sharp ocular motions, called saccades (Javal, 1878), which dominate the visual search behavior. There is an intimate relationship between the visual system and ocular motion. Incessant saccades pose a considerable challenge to the visual system which gets little time to process each fixation. More so, saccades bring substantial variation in the image statistics between successive fixations (Sherman and Guillery, 2006).

3.1.1 Saccade

Our visual search behavior is bounded by the anatomy of the sensory organ. The retina possesses a small dimple, called the fovea (Rochon-Duvigneaud, 1907), densely packed with photoreceptors. This region is spatially limited and yet it renders much of our colorful and detailed visual experience. It requires constant ocular motions to align objects of interest with the fovea. When an ocular motion displaces the retina, the visual cortex, which is organized retinotopically, abruptly has to encode a different region of space. The visual system has the complicated task of building a coherent reality from a stream of short fixations punctuated by sharp eye movements. Most researchers studying saccades have been fascinated by the

question of integration. In this paper, I addressed the complementary question of segmentation.

Continuity. Saccadic eye movements are a prevalent part of our visual search behavior, and yet they leave little conscious traces. This paradox has fueled a lot of research on the question of visual continuity (Wurtz, 2008), and it was uncovered that the processing of a visual stimulus is modulated by a corollary discharge emanating from the oculomotor system (Sommer and Wurtz, 2008).

Around saccadic eye movements, neuronal responses become more fluid. For example, saccades are associated with remapping (JR Duhamel and Goldberg, 1992), which is a transient shift in the neuronal receptive field location that anticipates the post-saccadic state. This phenomenon likely involves several mechanisms (Neupane et al., 2016) and shares an important link with attention (Cavanagh et al., 2010). Saccades cause strong disturbances in the visual system, which the brain must actively manage (Ibbotson and Krekelberg, 2011).

Suppression and Enhancement. Saccades entail a widespread biphasic modulation of the neuronal sensitivity (Reppas et al., 2002). The first phase consists of a suppression of the neuronal responses during the saccade (Matin et al., 1972; Diamond et al., 2000), in a form of active inattention (Zanos et al., 2016). The second phase is an enhancement of neuronal sensitivity post-saccadically (Ibbotson et al., 2007).

Resetting the Visual System. Some psychophysical evidence using bistable stimuli shows that saccades eradicate past perceptual states of ambiguous figures (Ross and Ma-Wyatt, 2004). Another experiment using real and simulated saccades

has shown that the magnitude of the influence from the preceding stimulus is significantly reduced by an eye movement (Paradiso et al., 2012). The authors suggest that saccades play an important role in resetting perception for each fixation. Also, eye movements can increase the ability of the visual system to segregate trans-saccadic stimuli as separate perceptual objects (De Pisapia et al., 2010).

An electrophysiological investigation of trans-saccadic contrast adaptation in V1 neurons reported that there was no complete reset from the previous fixation (Guez, 2015). Nevertheless, this study revealed an increase in the operating range and an improvement in the discriminability between contrasts following an eye movement.

3.1.2 Adaptation

To deal with the wide dynamic range and the spatial redundancy contained in natural scenes, neurons constantly adjust their response to the local statistical properties (Rieke and Rudd, 2009). Adaptation is a hallmark of sensory system (Wark et al., 2007). It is present at virtually every time scale, from milliseconds to millennia, and it likely involves multiple mechanisms (Whitmire and Stanley, 2016; del Mar Quiroga et al., 2016; Abbott et al., 1997). My experiments focus on the momentary contrast adaptation that occurs within the time frame of a natural fixation, also called contrast gain control or normalization (Albrecht et al., 2003).

3.1.3 Hypothesis

I asked if the aftereffect of adaptation persists across a saccade or if each fixation starts anew. Is visual adaptation modulated by ocular motion? My hypothesis is that ocular motion plays an important role in resetting the visual system on each fixation. To answer this question, I recorded cortical visual neurons of awake

macaques performing an oculomotor task. The empirical evidence gathered shows that saccades release the aftereffect from adaptation to a pre-saccadic stimulus in order to facilitate the bias-free processing of post-saccadic stimuli.

In the delayed post-saccadic probe experiment, I get to verify if the impact of the saccade is restricted temporally, which allows making an important distinction. I found that the saccadic modulation is transient, the aftereffect of adaptation is not simply cancelled.

3.2 Methods

Two adult rhesus monkeys, one male (Monkey P, *Macaca fascicularis*) and one female (Monkey A, *Macaca mulatta*) took part in this study. All aspects of the experiments were approved by the Animal Care Committee of the Montreal Neurological Institute and were conducted in compliance with regulations established by the Canadian Council of Animal Care. Surgeries were performed under general anesthesia (1-2 percent isoflurane gas) with standard sterile techniques. Both animals were initially implanted with titanium head posts to stabilize their head movements during training and experiments. After recovery, the monkeys were acclimatized to the lab and primate chair (Crist Instruments) before training began. The animals were first trained to perform a simple visual fixation task that facilitated receptive field mapping, followed by the main behavioral paradigm: the trans-saccadic adaptation task.

Visual Stimuli. Visual stimuli were back-projected using a specialized DLP LED projector (Propixx, VPixx Technologies). The screen was placed at a viewing

distance of 83 cm and covered about 80 degrees of visual angle. The entire psychophysical experiment was executed using MonkeyLogic (Asaad et al., 2012). All visual stimuli were presented against a neutral grey background. For the main results reported here, the visual probe consisted of a bar of varying contrast presented in the neuron's receptive field. The size of the stimulus was tailored to maximized the firing rate of the most units as possible, which varied with eccentricity of the RF (Gattass et al., 1988). On a given trial, the stimulus contrast was drawn from 8 levels, logarithmically spawning the range between 0 (no contrast, grey on grey) and 1 (full contrast, black on grey) as follows: $[0, 0.05, 0.1, 0.2, 0.35, 0.5, 0.75, 1]$.

Eye Tracking. The eye position was monitored at 1 kHz using an infrared eye tracker (Eyelink; SR Research). The saccade onset and offset were taken as the moment that gaze left the first fixation target and was capture by the second, respectively. Outlier saccades, for which the duration between those two events was more than 55 ms, were removed offline (Monkey P 0.3%; Monkey A 3%).

3.2.1 Trans-Saccadic Adaptation Task

The structure of the main behavioral paradigm, adapted from (Paradiso et al., 2012), is shown in Figure 3–1. Its two trial types allow me to compare the responses of V4 neurons to the same visual stimulus, with and without an intervening saccade and with or without adaptation. All trial types were presented in one interleaved block. The goal of the experiment was to assess the effect of adaptation to a strong adapter stimulus on the neuronal processing of a subsequent probe stimulus in a time scale that is relevant to perception.

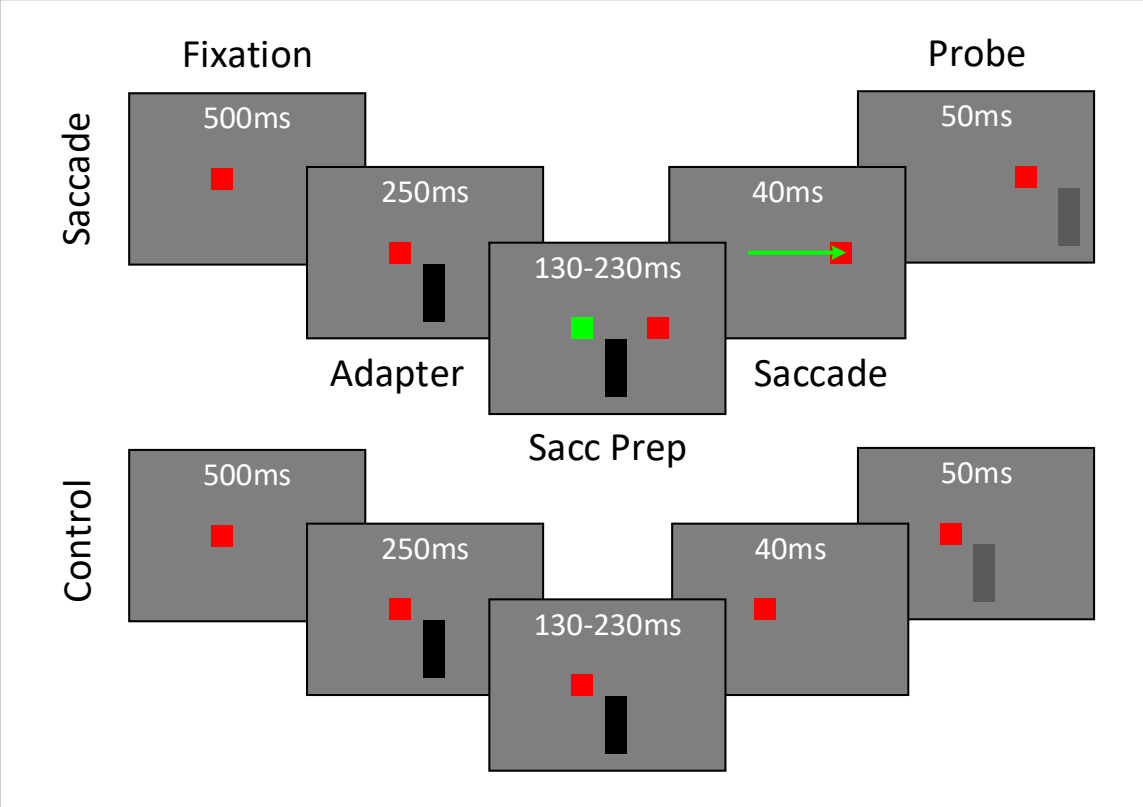


Figure 3–1: **Experiment in Details.** Every trial begins with the monkey fixating red square target for 500 ms. In half of the trials, an adapter stimulus is shown for at least 250 ms. In the saccadic condition, the green square and arrow represent the movement preparation (Sacc Prep) and the saccade, respectively. Then, a probe stimulus of varying contrast is presented for 50 ms. The control condition is designed to have matching timing and retinal stimulation. It includes a variable adapter time to simulate the saccade preparation latency and a brief recovery between the adapter and probe stimulus.

In all conditions, the monkey initiated a trial by acquiring the central fixation by directing its gaze to within 1.5°of the fixation target (0.5°) for at least 500 ms. Then, the monkey maintains fixation for 250 ms while an adapter is presented in the neuronal receptive field. The duration of the adapter maximizes the effect of

short-term adaptation, which plateaus after 200 ms (Shapley and Enroth-Cugell, 1984), while approximating the timecourse of natural eye movements (Henderson and Hollingworth, 1998).

Saccade Trials. During saccade trials, the fixation target then vanished, and a saccade target appeared, located 15° ipsilaterally on the horizontal plane. This instructed the monkey to make a saccade. The adapter stays on during the variable saccade preparation period, until initiation is detected. After the saccade landed on the target, a short probe stimulus (50 ms) of varying contrast was presented in the neuron's current receptive field. The animal then needed to maintain its gaze for 500 ms to receive a liquid reward. Importantly, the adapter and the probe stimuli are spatially separated by the saccade vector, so they fall on the same retinal location.

Simulated Saccades. On simulated saccade trials, no saccade target appeared and the animals were not required to make saccade. However, the visual stimuli were shown in the same retinotopic location and with the same timing as in saccade trials. Specifically, the adapter is kept on for a variable period corresponding to the saccade latency (normally distributed with $\mu = 180\,ms$ and $\sigma = 25\,ms$). Next, the adapter is turned off for 40 ms, simulating the stereotypical duration of a saccade. Finally, the probe stimulus is presented for 50 ms and the monkey maintains fixation for an additional 500 ms before the end of the trial.

Post-Saccadic Stimulus Timing. In the non-delayed paradigm, the probe stimulus is designed to appear immediately once the second fixation is acquired after the saccade. This relates to natural vision while giving a strict control on the

stimulus duration. In a second data set, the stimulus presentation was delayed by 100 ms post-saccadically. Both data set were analyzed separately.

3.2.2 Electrophysiological Recordings

Once the animals became proficient at their task, they underwent a sterile surgical procedure to implant a recording apparatus. Monkey P was equipped with a chronic 10 x 10 microelectrode array (Utah array; Blackrock Microsystem) over a peripheral portion of the dorsal portion of area V4 (described previously (Neupane et al., 2017; Zanos et al., 2016)). Monkey A was implanted with a recording cylinder above the ventral portion of area V4. Daily acute recordings using 32 channels linear electrodes (V-probe; Plexon) were used to acquire neuronal signals. Broadband neuronal signals were recorded using a standard data acquisition system (Intan). The linear electrode was sampled at 30 kHz while the array was sampled at 20 kHz. Subsequently, a digital filter was applied to bandpass the raw signal between 300 Hz and 3000 Hz. Then, for each channel, the multi-unit neuronal action potential was isolated by using the *wave-clus* algorithm (Chaure et al., 2018), which computes the MUA by thresholding (4σ) the bandpassed signal. The resulting spiking events were stored at 1 kHz.

The spike train was further processed to obtain a smooth spike density function by filtering the data using a dual linear kernel composed of a Gaussian component ($\sigma = 25\,ms$) and an exponential component ($\tau = 25\,ms$). This asymmetric kernel grants the smoothing power of the Gaussian while the temporal consistency is ensured by the exponential, producing an essentially causal Gaussian filter that better approximates the continuous input each neuron receives from integrating many synaptic signals at its dendrites.

3.2.3 Data Analysis

Modeling the Contrast Response Function. The contrast response function (CRF) was characterized using the modified hyperbolic ratio of *Naka-Rushton* (Peirce, 2007):

$$R = R_{max}\frac{c^n}{c_{50}^{sn} + c^{sn}} + B$$

Here, the response R of a neuron, is defined as the peak of the transient response in the period of 50 ms to 250 ms following the stimulus presentation. It is a function of the stimulus contrast c, the parameters R_{max} and c_{50}, the asymptotic response and semi-saturating contrast, the exponents n and s and the baseline firing rate B. When $s = 1$, the equation simplifies to the traditional Naka-Rushton, and the parameters have an intuitive interpretation. Nevertheless, adding a degree of freedom, so that the suppressive exponent s can vary at a different rate than the excitatory exponent n, is necessary to capture the non-monotonic supersaturating contrast response exhibited by some neurons (Sani et al., 2013) (see figure 3–2a for an example).

Fitting the Model. To fit the contrast function to the neuronal response, I began by isolating the peak of the transient response for each trial. A baseline firing rate was taken from the stable response during fixation, 500 to 250 ms before the adapter presentation. Then, the baseline was subtracted from the peak activation and I noted the extremum of the response across all conditions and contrasts for each neuron. Additionally, the transient caused by the high contrast adapter sets a lower bound on the maximum. Next, the trials were normalized, by removing the minimum and dividing by the range, so that the responses were constrained to be between 0

and 1, ensuring valid comparison between neurons. Finally, the contrast function was fit to the response by using a non-linear least-squares algorithm (Dennis Jr, 1977). To avoid runaway parameters and to limit the multiplicative space of the exponential arguments, n and s were constrained to be between [1, 4] and [0.5, 2] respectively.

Quantifying Contrast Adaptation. I quantified the effect of adaptation as the difference in the neuronal response between the adapted and unadapted conditions. Adaptation can modulate the neuronal response in two ways: a decreased amplitude, often called response gain control, or diminished contrast sensitivity. Parametrically, the amplitude of the response is represented by r_{90}, the 90% of the fitted Naka-Rushton maximum, which is more accurate than the true maximum for neurons that have an asymptotic saturation phase. Sensitivity corresponds to the capacity to distinguish the stimulus contrast and can be formalized by the range, the difference between the extrema of the fitted CRF. I concentrated my study on the variation in the response amplitude because it has the most stable influence on the neuronal response (see also supplementary figure 3–7).

Statistical Hypothesis. For each neuron in the population, I quantified the effect of adaptation by taking the difference in responses between the adapted and unadapted conditions, for the saccade and fixation trials independently. Then, I performed a student t-test to reject the null hypothesis that the data has a mean of zero (i.e., there is no difference between the adapted and unadapted responses). I did a paired test to assess whether the magnitude of the influence was different in the saccade and fixation conditions. To illustrate my results succinctly, I also computed a measure of *saccade recovery*, which is the difference in the effect of adaptation

between the two conditions. Another point of consideration was that the saccade could modulate the processing of the stimulus independently from the adaptation. Thus I added a *saccade effect*, which is the difference between the saccade and fixation conditions when no adapter is present.

3.3 Results

Visual Neurons. I recorded the activity of 91 V4 neurons (58 from monkey P, 33 from monkey A) using the non-delayed paradigm. An additional 103 V4 neurons (all from monkey A) where recorded in the delayed paradigm. This set consists of 47 neurons that responded to bar stimuli, as in the first experiment, as well as 56 that preferred flashed or drifting gratings. While the post-saccadic timing is different, the fixation control is unchanged in both experiments.

Exclusions. Before continuing further, the data set was trimmed by imposing restrictions on valid parameters. I removed any neurons that had a response range below 0.5 in the best condition; these neurons were either very noisy or dominated by their response to the adapter stimulus. For the same reason, I removed any neurons with a $r_{90} > 1$, which indicates an inappropriate fit. Finally, I also excluded any neurons that had a coefficient of determination (R^2) below 2.5%. Ultimately, these neurons had a weak response to the contrast of the target stimulus and added more noise to the data set.

For the first experiment, 43% (24 monkey P; 15 monkey A) of recorded units have a significant response to contrast and are included in the main analysis. The second experiment contains 78% (80 monkey A) of neurons that are significantly modulated by contrast.

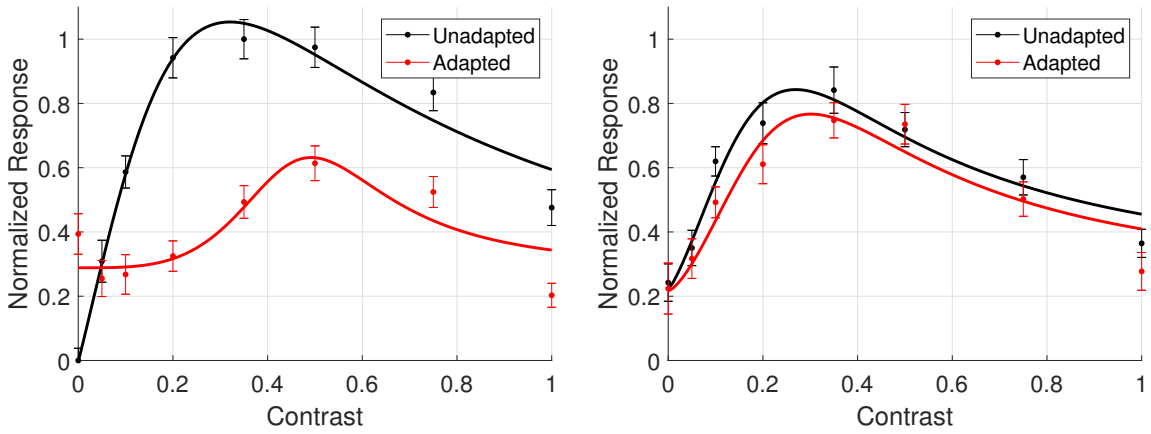
3.3.1 Aftereffect of Contrast Adaptation

The central interest of this paper is to investigate the interaction between ocular motion and visual adaptation. My hypothesis is that active modulation of the visual system provided by the saccade allows optimal processing of the post-saccadic stimulus. In order to address this thesis, the first step is to assess the influence of the aftereffect of adaptation to a high contrast adapter stimulus on the processing of the probe stimulus. This is done by comparing the contrast response function of cortical neurons in a steady fixation control, with or without an adapter.

Typical Contrast Response Function. Our main results and analysis are founded on evaluating how the contrast response function is modulated by the task variables, which are the adapter and the ocular motion. Figure 3–2 shows the contrast response function for a representative example neuron. In each condition, I compared how the adapter distorted the neuronal response (red) in comparison to the unadapted response (black).

The black line in figure 3–2a is the neutral neuronal response, as it is unaltered by the task variables. This singular example highlights the normalization within the 0 to 1 range, and also presents the characteristic non-monotonic contrast response of V4. The red line captures the effect of the adapter stimulus on visual response to the probe stimulus. Foremost, the aftereffect of adaptation is characterized by a decrease in the response amplitude, which is reflected in a vertical, downward shift in the CRF. Additionally, the adapter also reduces the contrast sensitivity to the probe stimulus, which manifests several ways in the CRF: a horizontal rightward shift in the optimal contrast, a dulled slope and a compressed response range. In fixation,

there is a profound influence from the adapter stimulus on the processing of the probe stimulus, the qualitative effects of adaptation are noticeable in the response of a single neuron.



(a) **Fixation Control** (b) **Saccade**

Figure 3–2: **CRF for an example neuron**. The points and whiskers denote the mean and s.e.m. of the normalized responses for each contrast level. The solid lines correspond to the Naka-Rushton fits. In black, the unobstructed neuronal response. In red, the CRF when the adapter is present. When comparing the saccade condition with the fixation control, it is apparent that the aftereffect of adaptation is minimized by the eye movement. In fixation, the adapter has a large impact on the amplitude of the response. There is also an noticeable shift in the response function. On the contrary, in the saccadic condition the aftereffect is minimized and the CRF has a similar shape to the unadapted condition. In this example neuron, the amplitude is reduced for both saccadic trials, but there is no significant saccadic modulation in unadapted trials at the population level.

Adaptation in Fixation. The effect of adaptation on the population follows what I illustrated with the example neuron. In the supplemental figure 3–6, I depict the difference between the adapted and unadapted responses for the whole population of neurons. In one word, the impacts of adaptation are pandemic. Broadly, the population suffers a reduction in the response amplitude (3–6a). Although there is

some variability in the intensity of adaptation, it has a uniform impact across animals and stimuli. This supports the notion that adaptation is a fundamental property of sensory neurons.

I combined together the population parametric evidence to quantify the relative strength of adaptation in fixation, summarized in figure 3–3. Adaptation has a significant influence on the neuronal response rate ($\mu = -0.21, \sigma = 0.21, P : 2.6 \times 10^{-19}$). This suggests that contrast discrimination of the probe stimulus is impaired by the high contrast adapter stimulus.

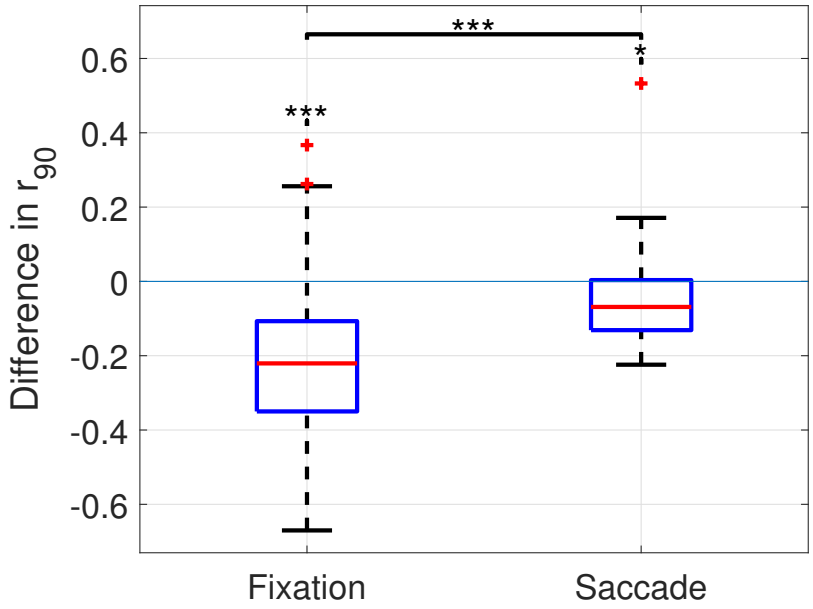


Figure 3–3: **Aftereffect of adaptation on response amplitude.** Adaptation causes a significant decrease on the response amplitude ($p-value < 10^{-3}$) in fixation. But the evidence is weaker in the case of trans-saccadic adaptation, with $p-value < 0.05$. Comparison of both condition reveals that the saccade significantly modulates the activity of the neuron to attenuate the aftereffect of adaptation ($p - value < 10^{-3}$).

3.3.2 Saccadic Release from Adaptation

From the previous results, I have established in a time scale relevant to ocular motion that contrast adaptation has a powerful impact on sensory processing. In the absence of modulation by the oculomotor system, one would expect the visual response to be similarly obstructed by adaptation. My data indicate that this is not the case. It is apparent, even at the single neuron level (figure 3–2b). The stranglehold of the adapter is minimized by the action of the saccade. In the saccadic condition, the adapted neuronal response (red) is qualitatively similar to the unadapted response (black).

In the supplementary figure 3–6b, I present the scatter of parameters for the saccadic condition. There is no pattern that separates both animals. Compared to the fixation control, the distribution of the population parameters is clustered close to the reference line. This suggests that neuronal responses are disconnected from pre-saccadic adaptation.

Overall, the aftereffect of an adapter persists trans-saccadically. Although less pronounced, the effect of the adapter on the probe stimuli is suppressive (figure 3–3; $\mu = -0.05, \sigma = 0.14, P : 0.03$). But importantly, the saccadic eye movement attenuates the strength of adaptation (P: 4×10^{-7}). This implies that the visual system is actively modulated by ocular motion such that the aftereffect of adaptation decreases trans-saccadically, allowing for optimal processing of the post-saccadic stimulus.

In the example neuron presented earlier (figure 3–2), it appears that the saccade attenuates the neuronal response, even in the absence of an adapter. I tested at the population level and found no evidence that there is a difference between the

responses in the saccade and fixation control (Figure not shown, Response Rate: mean: -0.03, SD: 0.18; P: 0.2).

3.3.3 No Recovery for Delayed Post-Saccadic Probe

I recorded a data set in monkey A where the probe stimulus presentation was delayed after the saccade. It granted me the opportunity to refine my interpretation of the oculo-visual interaction. If the aftereffect of adaptation was cancelled by an ocular motion, one would expect that late stimulus presentation would also benefit from a saccadic release. On the contrary, it is possible that the ocular motion opens an optimal window for the visual input, temporally allowing bias-free processing of the post-saccadic stimulus. My findings agree with the second explanation, as delayed stimuli show a strong influence from the pre-saccadic adapter.

In this data set, I cannot reject the null hypothesis that there is a difference in the adaptation aftereffect between the fixation control and saccade condition (Response Gain P: 0.3 ; Contrast sensitivity: P: 0.4). In all conditions, the parametric evidence shows that the adaptation represses the neuronal response: (figure 3–4, Fixation: $\mu = -0.17, \sigma = 0.2, P : 5 \times 10^{-11}$; Saccade: $\mu = -0.14, \sigma = 0.21, P : 7 \times 10^{-8}$). These results favor the interpretation that eye movements prime visual neurons to an optimal state immediately following the saccade, and do not simply erase the previous state.

Despite having a longer recovery period, adaptation preserved a strong impact on delayed probe stimulus. On the other hand, there is an enhancement of the neuronal response to the delayed post-saccadic stimulus when no adapter is presented (figure not shown, Response Gain: $\mu = 0.15, \sigma = 0.15, P : 1 \times 10^{-13}$)

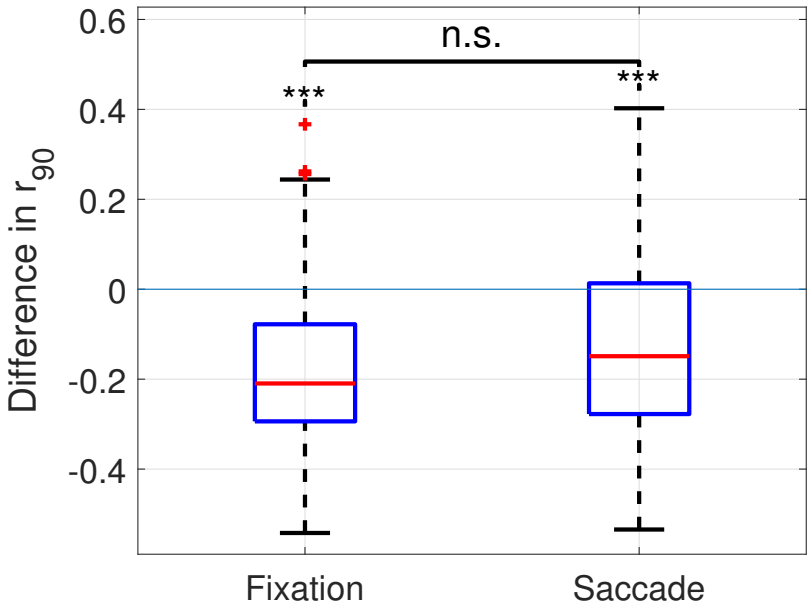


Figure 3–4: **Aftereffect of adaptation on delayed post-saccadic probe.** In both the fixation and the saccade condition, neuronal responses are significantly suppressed by adaptation ($p - value < 10^{-3}$). There is no significant difference in the aftereffect of adaptation in fixation and for delayed probe.

3.4 Discussion

The objective of this paper was to study the connection between the oculomotor and visual systems. To do so, I set out to investigate if the aftereffect of contrast adaptation persists across a saccade. My results demonstrate that there is a modulation of adaptation by the saccade. In summary, I found that the aftereffect of adaptation is significantly reduced by an eye movement (figure 3–5). A stimulus presented immediately after the saccade is decorrelated from the adapter. However, the aftereffect of adaptation is not cancelled by the saccade, for delayed post-saccadic stimuli are still affected by adaptation.

Adaptation represents a form of short-term memory (Gerstner et al., 2014) in a recurrent network, and a complete state reset would be detrimental to the formation of a continuous stream of consciousness. Instead, ocular motion temporally opens a clean slate for the visual system, allowing optimal processing of the post-saccadic stimulus. In the absence of a post-saccadic stimulation, the aftereffect of the adapter, which is still encoded in the reverberation of the network, seize the population dynamics once more. It is possible the phenomena observed is related to post-saccadic enhancement of the neuronal response.

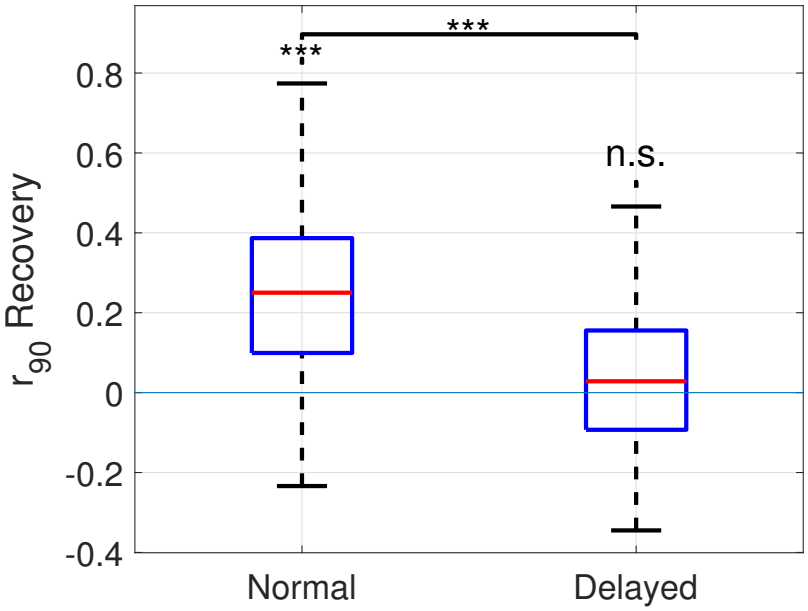


Figure 3–5: **Recovery from adaptation**. Re-plotted data from figure 3–3 and 3–4, recovery is the difference between the saccade and the fixation aftereffect. In the normal condition, there is a releases from the aftereffect of adaptation following an eye movement($p - value < 10^{-3}$). However, there is no such recovery in the delayed post-saccadic probe experiment. I conclude that ocular motion modulates the visual system, but adaptation is not simply erased by the saccade.

Eye movements Modulate Contrast Response. Our observations agree with the major idea reported by other investigators: the influence of a preceding stimulus is reduced by an eye movement. However, I cannot say that saccades reset the visual system (Paradiso et al., 2012), at least not entirely. Nevertheless, my findings are consistent with the notion that eye movements can increase the ability of the visual system to segregate trans-saccadic stimuli as separate perceptual objects (De Pisapia et al., 2010) and in concordance with Guez (2015) who reported no complete reset from the previous fixation, but an increase in the operating range and improved discriminability between contrasts following an eye movement. I have emphasized that there is a transient enhancement at the onset of fixation, in agreement with Rajkai et al. (2007), as if the eye movement was priming the system for a new visual input.

In the absence of an adapter, I found the contrast response to be enhanced in the delayed post-saccade experiment. This is consistent with Knöll et al. (2011), who reported a post-saccadic increase in contrast sensitivity, with a peak effect occurring some 100 ms after the completion of the eye movement. However, they link the effect to retinal motion, distinctly from other mechanisms that require oculomotor input. A meta-study (Ibbotson and Krekelberg, 2011) shows postsaccadic enhancement persists for 200ms.

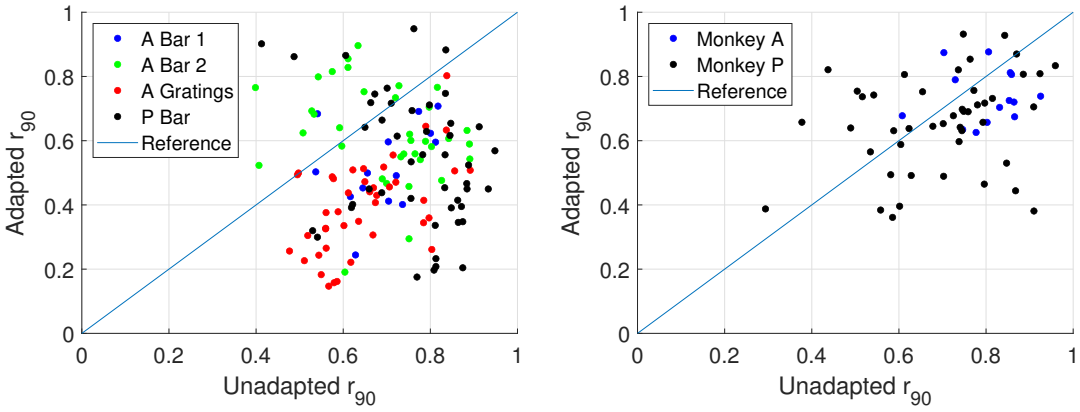
Experimental weakness. Quantifying contrast sensitivity by fitting contrast response function to single neuron is a doomed exercise for a simple reason: when a neuron responds poorly to the probe stimulus, its response is dominated by noise. Thus, the very effect I am trying to measure, the loss of contrast sensitivity, leads

to instability in the fitted parameters. The worst offenders are neurons that have the most drastic influence from adaptation. Some units have no response to the probe following adaptation, in which case the parametric approach becomes unstable. Objectively, these units have the strongest effect and yet it eludes quantification. In supplemental figure 3–7, there is an example of this type of shortcoming.

Empirically, my principal observations were based on how the amplitude of the neuronal responses varied with the task variables. But this is just one part of the puzzle. There is much more nuance about the response of neurons than the firing rate. Understanding of visual perception is limited in the recording of single neurons.

Conclusion. I demonstrated that the oculomotor and visual systems work in close coordination. There is an active mechanism that allows for the brain to release adaptation and begin each fixation anew. Saccades modulate the neuronal state to be in an optimal position to process post-saccadic stimuli, but there is no hard reset following a saccade. The positive impact of the saccade is restricted to probe stimuli presented immediately after the eye movement, as delayed post saccadic probes have a significant adaptation aftereffect. This signifies that the aftereffect of adaptation is not erased trans-saccadically. Instead, active modulation from the oculomotor system temporarily sets the visual system in a condition that permits bias-free processing of the post-saccadic stimulus.

Supplementary Figure



(a) **Fixation** (b) **Saccade**

Figure 3–6: **Scatter of the parameters for each neuron in the population.** Points below the reference line indicate that the adapter suppresses the response to the probe stimulus. The effects of adaptation are ubiquitous in fixation. In the saccadic condition, points are clustered to the reference line, implying that the aftereffect of adaptation is weak in that case.

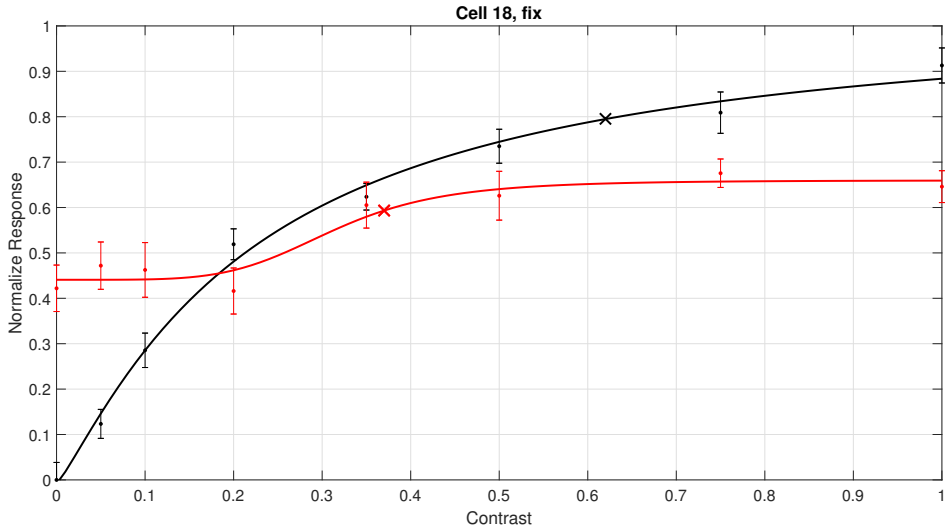


Figure 3–7: **Parametrize response gain and contrast sensitivity.** The point of r_{90} (x) characterize the strength of the response. However, the associated C_{90} is not always a good representation of the contrast sensitivity. Compared to the unadapted (black), the contrast response function is shifted leftward in the adapted condition (red). Parametrically, this shift in C_{90} would indicate an increase in sensitivity following the adapter. Whereas it is obvious that this neuron would be less effective at discriminating contrast.

CHAPTER 4
Adaptation Attractor Dynamics and Saccades

In chapter 3, my study of adaptation has focused on single-unit behavior. The effect of adaptation is inferred by examining how it impacts the coding of individual neurons, but adaptation goes beyond traditional fatigue-based descriptions of isolated units (Solomon and Kohn, 2014). The brain is more than the sum of its individual neurons. As I alluded in the introduction, there is a need to reorient our interpretation of the brain in terms of whole population dynamics. del Mar Quiroga et al. (2016) predicted that adaptation phenomena could emerge from attractor dynamics in a recurrent network. I tested this hypothesis through state-space analysis, which is a technique to illustrate population responses as trajectories in neural state-space.

4.1 State-Space Analysis

The method I employed was to project the high-dimension response manifolds into low dimension axes that capture the variation due to the task variables (Mante et al., 2013). The procedure begins by collecting linear regression models to determine the interaction between each task variable and the recorded units.

First, I z-scored the responses of each unit: $r = \frac{r-\mu_r}{\sigma_r}$, where the mean and the standard deviation were pooled from all trials in all conditions. Simple linear models

were fit to each unit i and time point t independently:

$$r_{i,t}(k) = \beta^1_{i,t}\text{contrast}(k) + \beta^2_{i,t}\text{adapter}(k) + \beta^3_{i,t}\text{saccade}(k) + \beta^4_{i,t}$$

with the regression coefficients estimated as:

$$\beta_{i,t} = (F_i F_i^T)^{-1} F_i r_{i,t}$$

where F_i is a matrix containing the task parameters (contrast, adapter present/absent, and saccade present/absent) for each trial.

Next, I applied principal component analysis (PCA) to a data matrix X of size $N_{units} \times (N_{conditions} * T)$ to get the principal components (PCs) v_a of length N_{units}, where each column of X corresponds to the averaged responses for a unit under all conditions and time points. I defined a de-noising matrix D by keeping the first $N_{pc} = 6$ so that:

$$D = \sum_{a=1}^{N_{pc}} v_a v_a^T$$

That allowed to focus the analysis and reduced the subspace to its most informative dimensions by taking $X_{PCA} = DX$.

A fundamental conceptual step is viewing the regression coefficients not as properties of individual units, but as directions in the state-space along which the underlying task variables are represented at the population level. This is done by rearranging the entries of $\beta_{i,t}$ into the vector $\beta_{v,t}$ (of length N_{units}) which corresponds to a direction in the state-space that accounts for the variance in the population response at time t due to the task variable v. These coefficient vectors can be de-noised using

the matrix D:

$$\beta_{v,t}^{pca} = D\beta_{v,t}$$

and transformed into a time-independent representation by taking the time point that maximizes the magnitude of the vector:

$$\beta_{v}^{max} = \beta_{v,t^{max}}^{pca}$$

with:

$$t^{max} = argmax_t \|\beta_{v,t}^{pca}\|$$

Finally, the regression vectors were orthogonalized via QR decomposition:

$$B^{max} = QR$$

Where Q is orthogonal, and R is an upper triangular matrix. The columns of the matrix Q correspond to the orthogonalized regression vectors $\beta_v^{\perp}$ or task-related axes. They span a regression subspace which explains distinct portions of the variance in the response. The full model is overdetermined: the task features *contrast* and *adapter* were both responsible for variation in the same direction, corresponding to visually-driven activity. To clarify the interpretation, I therefore chose to keep only the adapter variable for this part.

The last step was projecting the responses onto the orthogonal axes to obtain the time series:

$$p_{v,c}(t) = {\beta_v^{\perp}}^T X_c$$

4.2 Results

State-space analysis works by representing the activity of a whole population of neurons as a point in a high dimension space. The approach is to find a meaningful projection to sketch the brain state in a digestible way. This can reveal dynamic patterns of activation across the population. Trajectories are time series that show the evolution of the neuronal population throughout the trial.

For the visualization that I present in this section, neuronal responses to visual stimulation are illustrated by horizontal motion; in other words, the abscissa is the dimension of the visually driven activity. The ordinate axis has a less straightforward interpretation. It represents the dimension along which variation in the data is caused by condition (saccade or fixation). It is not limited to the activity directly around the saccade, but rather encodes the differences between the two types of trials, capturing the variability in the neuronal response that is orthogonal to the visual dimension. I will refrain from attaching a significance to vertical motion in the neuronal trajectories. Suffice to say that it provides an apt canvas to project the high dimensional population response.

Given what is known contrast adaptation, I can make some predictions regarding the form of the neural trajectories. Since visual responses are transient, trajectories will be characterized by short-burst motion throughout the subspace. Further, the aftereffect of adaptation will result in a reduction of the response amplitude to the probe, with only a partial effect when a saccade occurs between the adapter and the probe stimuli. If ocular motion applies an active modulation on the visual neurons, it might come to light in the neuronal trajectory surrounding eye movements.

In this section, I present three figures corresponding to three separate neuronal populations, for the delayed and non-delayed experiments in monkey A as well as the non-delayed experiment in monkey P. For monkey A, I approximated a neuronal population by pooling neurons recorded during sessions that used the same stimulus timing. Since this population is assembled gradually, across days, it lacks some of correlation structure present in a real population. However, the neurons grouped together come from a few real sub-populations, each of which have similar response profiles. In monkey P, the chronic array allows simultaneous recordings of a real population comprised of many neurons, albeit one that is an infinitesimal fraction of the whole brain.

In each figure, there are four time series representing the experimental conditions: a real or simulated saccade (fixation), each with or without an adapter. Each line is obtained by projecting the population-averaged trial on the neural subspace corresponding to the task variables. The time zero refers to the probe stimulus presentation. Every condition begins with the initial fixation, which is depicted in blue. This color indicates that neuronal activity is not modulated by any task variable.

The Adapter. The adapter provides the first perturbation to the neuronal population, which affects the two trajectories where the adapter was shown. It is illustrated, in red, as a large loop in the visual dimension. Although the adapter is presented for more than 300 ms, the neuronal dynamics evolve more quickly. After the initial response to the visual stimulation, the neuronal dynamics do not go back to the initial state but instead stabilize into an attractor state. The population response stays in that state while the stimulus is turned on, and in the absence of

ocular motion, it lingers in this state on after the adapter disappears (highlighted in black).

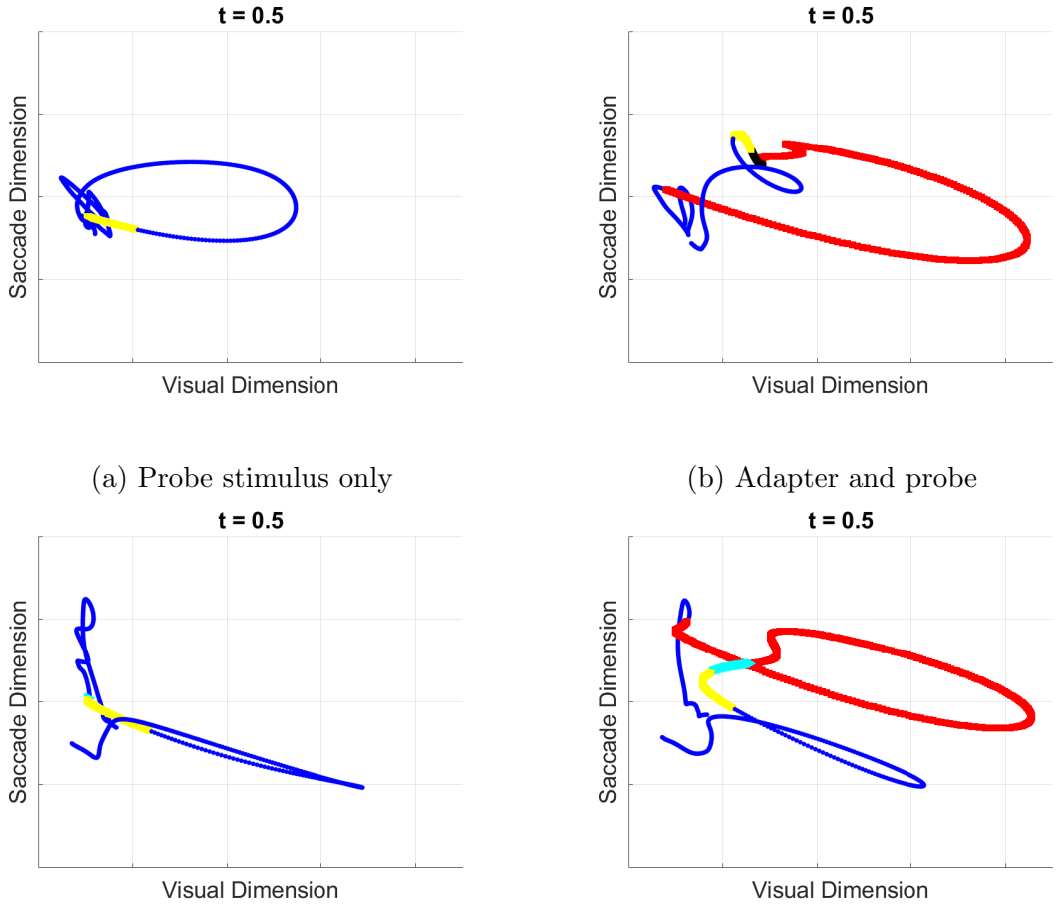
The Saccade. Ocular motion is present in two of the four trajectories (with or without the adaptation), illustrated in cyan. The saccade is very brief (50 ms), but it has a major impact on the neuronal dynamics. Notably in the case of pre-saccadic adaptation. The main implication that I want to emphasize is that the saccade dynamically liberates the visual system from the aftereffect of adaptation by pushing the neuronal manifold toward the neutral position.

The Probe. The central component of this study is the neuronal response to the probe stimulus, and how it is influenced by the preceding events. Accordingly, the trajectories have been synchronized such that the probe stimulus is presented at time zero. In yellow, the visual stimulation launches the neuronal trajectories in a motion that outlasts the duration of the probe. As with the adapter stimulus, the visual response to the probe is characterized by a transient loop through the subspace.

4.2.1 Monkey A Neuronal Trajectories

In figure 4–1, I present the trajectories for the non-delayed experiment for monkey A. The response to the probe stimulus is considerably diminished when it is preceeded by the adapter stimulus: namely, the neuronal trajectory goes in the wrong direction. Figuratively, some of the probe energy is used to drag the neuronal response out of the adapter attractor as the trajectory does a literal turn around. In comparison, the neuronal trajectory regains its un-adapted form when a saccade separates the adapter and the probe stimuli. The saccade actively pushes the neuronal dynamics

away from the adaptation attractor state and toward the neutral state. However, the saccade has a minimal impact on the neuronal response when there is no pre-saccadic stimulus.



(a) Probe stimulus only

(b) Adapter and probe

(c) Saccade and probe

(d) Adapter, saccade and probe

Figure 4–1: * **Monkey A Neuronal Trajectories** Every trajectory represents the evolution of the population of neurons throughout an averaged trial. It begins in a neutral position (blue). Then, the adapter (red) takes hold of two trajectories, bringing them into an attractor state after the initial visual transient. The saccade (cyan) actively pushes the neuronal response away from the attractor and toward the neutral state where the probe stimulus (yellow) can be processed normally.

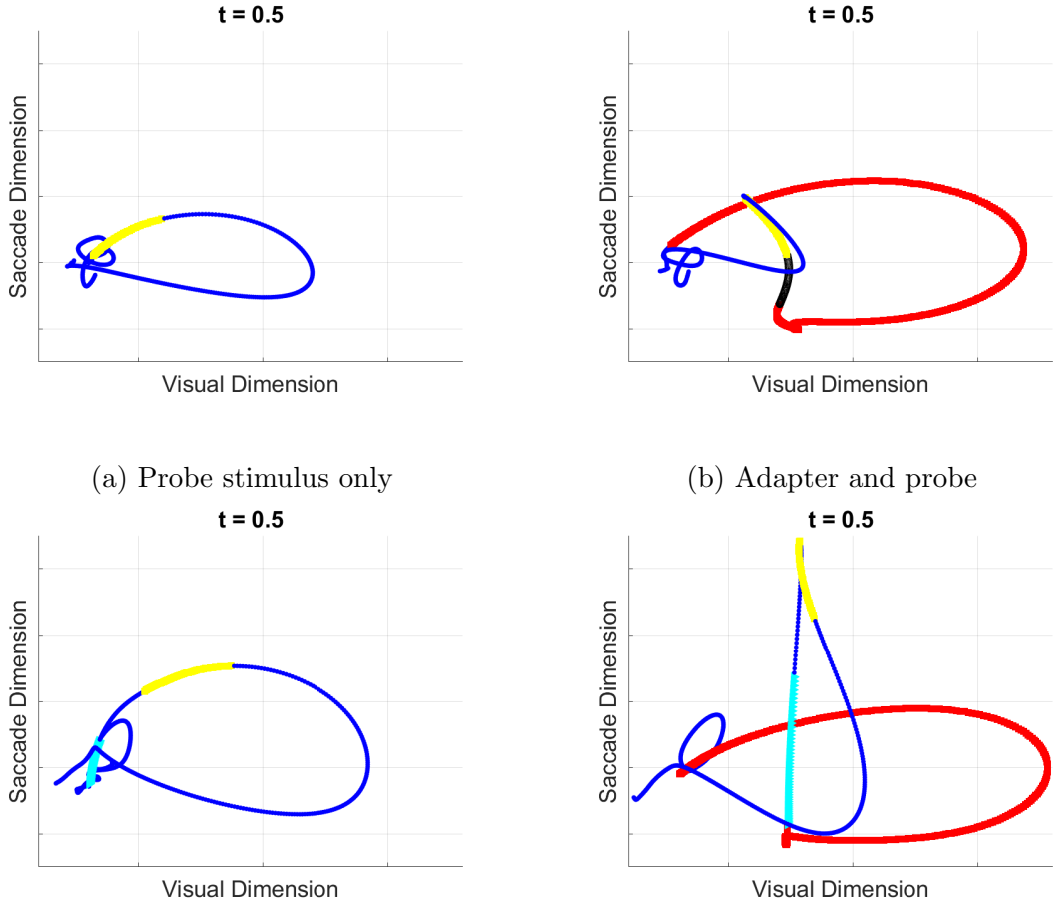
4.2.2 Delayed Probe Trajectories

Figure 4–2 shows the neuronal trajectories for the delayed probe experiment. The response to the adapter (red) is similar to before, as the neuronal trajectories loop through the subspace and settle into an attractor state. Next, the saccade (cyan) launches the neuronal dynamics in the saccade dimension. In the absence of a post-saccadic stimulus, the neuronal activity overshoots the neutral state. When the delayed probe comes, the neuronal trajectory is going in the wrong direction and the visual response is inhibited. In comparison, in the absence of ocular motion (black), the neuronal response is much slower returning to the neutral state. In this figure, active modulation by the oculomotor system is apparent even without a pre-saccadic adapter. The neuronal activity is driven in the correct direction even before the probe stimulus. Perhaps this explains why we have seen an increased response amplitude in that condition.

4.2.3 Monkey P Population Trajectories

The neuronal trajectories extracted from monkey P population are presented in figure 4–3. Qualitatively, the effect of the adapter is similar to the other graphics. However, there is a marked difference in the effect of the saccade on the neuronal trajectories. In fact, while ocular motion is occurring (cyan) there is virtually no movement in the neuronal trajectories. Nevertheless, the post-saccadic probe has

* To view the dynamic content, you must have the Flash player installed on your computer and activate the 3d content in adobe acrobat reader by "trusting" the document.



(a) Probe stimulus only

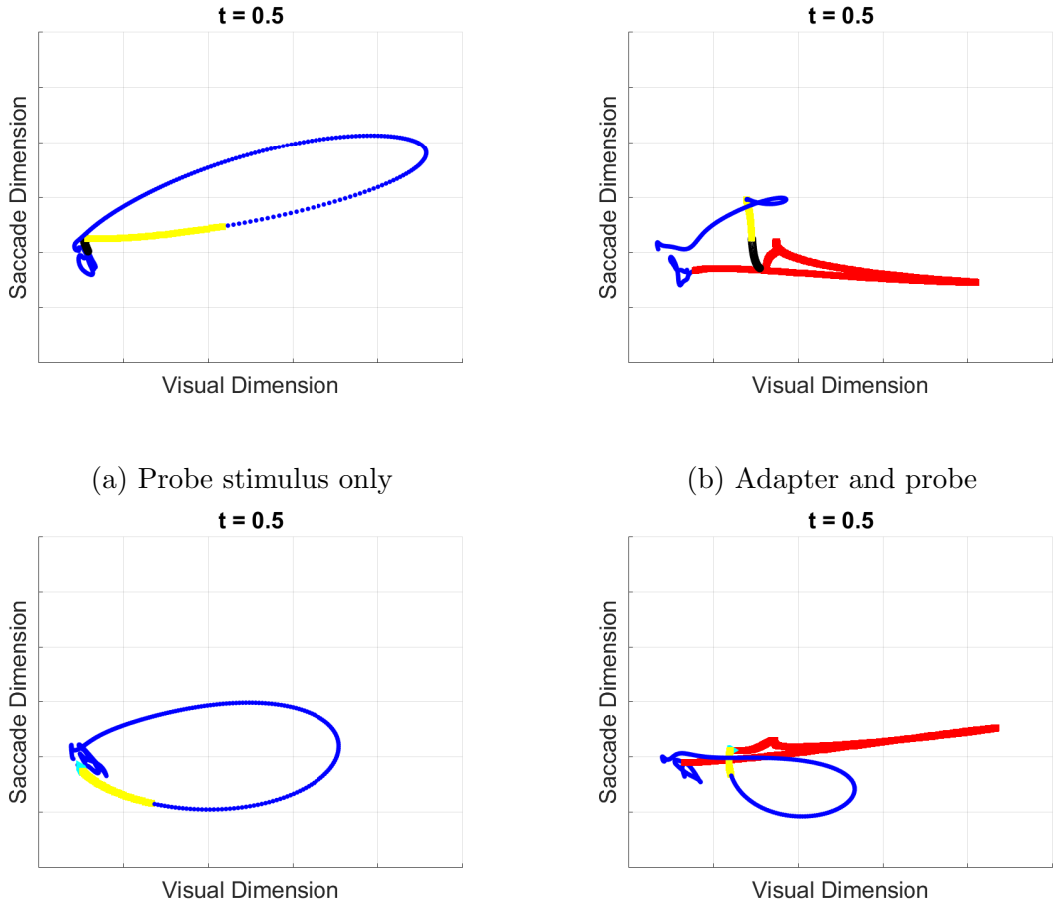
(b) Adapter and probe

(c) Saccade and probe

(d) Adapter, saccade and probe

Figure 4–2: * **Monkey A, delayed probe experiment**. Trajectories begin in a neutral position (blue). Then, the adapter (red) takes hold of two trajectories, bringing them into an attractor state. The saccade (cyan) actively pushes the neuronal response away from the attractor and toward the neutral state, but in the absence of an immediate post-saccadic stimulus, the neuronal trajectory continues to another state, and the processing of the probe stimulus (yellow) is altered.

partially recovered from the aftereffect of the adapter. It seems that the neuronal trajectory starts to diverge from the adapter attractor and toward a neutral state before the eyes move, during the saccade preparation interval.



(a) Probe stimulus only

(b) Adapter and probe

(c) Saccade and probe

(d) Adapter, saccade and probe

Figure 4–3: * **Monkey P Neuronal trajectories** begin in a neutral position (blue). Then, the adapter (red) takes hold of two trajectories, bringing them into an attractor state. There is no motion in the neuronal trajectories at the moment of the saccade (cyan). However, the trajectory evades the attractor state before the eye movement, in the saccade preparation period. The response to the probe stimulus (yellow) is partially recovered.

4.3 Conclusion

In this section, I illustrated the responses of populations of neurons as trajectories through a subspace designed to represent the task variables. The visual response consists of a loop through the neuronal subspace. Short-term adaptation is the mechanism that brings the neuronal response from the initial large-amplitude transient to the subsequent attractor state.

When the adapter is presented during fixation, the neuronal response to the succeeding probe is attenuated. In comparison, when there is ocular motion between the adapter and probe stimulus, the visual response is qualitatively similar to the unadapted post-saccadic response. The saccade modulates the neuronal trajectory to a state that allows the post-saccadic test stimulus (yellow) to be processed normally. The influence of the saccade can begin before the eye movement, in the preparatory period.

In the case of delayed stimulus presentation, in the absence of a test stimulus immediately after the saccade, the dynamics do not stay at the neutral location, which seems to hinder the processing of the late stimulus. The graphs are not directly comparable between populations as the projection dimensions are isolated independently.

These results exemplify the importance of the trajectory preceding the probe presentation. Vigorous responses occur when the neuronal trajectory is in sync with the visual stimulation. In contrast, when the neuronal trajectory leading to the probe stimulus is moving in the wrong direction, a weak response ensues.

CHAPTER 5
Discussion

Problematic. Neurons of the visual cortex are continually adapting to the local statistical properties of the image. Saccades pose a unique challenge by constantly reorienting the sensory organ. Suddenly shuffling the retinotopic input, breaking the correlation structure and leaving little time for the neurons to adjust. Yet, the visual system seamlessly transitions from one fixation to the next. I hypothesized that there must be an active mechanism that allows for the brain to release pre-saccadic adaptation to reset and begin each fixation anew. My interpretation of the data is that there is no hard reset following a saccade. Instead, the saccade actively modulates the neuronal state to be in an optimal position to process post-saccadic stimuli.

The Role of Saccades in Vision. Saccades disrupt visual representations of temporary states while enhancing representations that preserve learned stimulus contingencies (Ross and Ma-Wyatt, 2004). The role of saccades in perception is active and dynamic. Eye movements synchronize the visual system to a common onset transient, while simultaneously restoring the brain state for optimal processing. Because of the entanglement of the oculomotor system with the attention system (Goldberg et al., 2002; E. Irwin Robert D. Gordon, 1998), I am inclined to take this one step further. The choice of visual target is not random (Najemnik and Geisler, 2005), it could be that the brain selects a saccade target that can make or break

a representation. In other words, given a new scene, the visual system makes a prediction of the environment founded on fragmentary data. Subsequent saccades are taken to locations that maximize the ability to discriminate between competing hypotheses. A conscious representation, which is built up over time, is the result of the dynamic interplay between sensory and motor processes (Greenlee and Kimmig, 2019).

5.1 Mechanisms

Adaptation. Although plastic changes are certainly involved, a plausible candidate for the implementation of short-term sensory adaptation is the recurrent dynamic interplay between excitatory and inhibitory neurons (del Mar Quiroga et al., 2016). As demonstrated in chapter 4, adaptation can emerge from attractor dynamics at the population level. The response to a visual stimulus is transient. After an initial burst, neuronal trajectories rapidly evolve toward an attractor state.

Adaptation has similar effects throughout the visual cortex (Patterson et al., 2014). It is an intrinsic property of sensory processing, a canonical computation of the brain (Carandini and Heeger, 2012). Cortical circuitry incorporating adaptation can be modeled as divisive normalization (Kaliukhovich and Vogels, 2016) of the input, which occurs through horizontal cortical connections.

Saccade and Oscillation. In electrophysiological studies, Maldonado et al. (2008) have found an increase in the synchronization of neuronal responses in free viewing macaques following a saccade. As well, Rajkai et al. (2007) have demonstrated a transient cortical enhancement at the onset of fixation, as if the eye movement was priming the system for a new visual input. Further analysis revealed that

fixation onset was associated with neuronal oscillatory phases going into a highly organized state. They hypothesized that the phase concentration reflects modulation of the neuronal ensemble in preparation for new stimuli. This is consistent with the idea that oscillatory phase modulation could be a general mechanism to synchronize different information pathways (Lakatos et al., 2007). Oscillations may have the crucial role of coordinating the oculomotor and visual systems.

Cortical Travelling Wave. Networks of coupled oscillators naturally give rise to wave-like patterns (Heitmann et al., 2012). In particular, transient modulation of the strength of inhibition can create specific wave patterns in network of beta oscillators. Topology that supports both wave and synchrony can achieve rapid change in brain state, which is required by saccades. The visual cortex oscillate between two bistable states: a state of perceptual scanning, tied to a traveling wave and a state of perceptual recognition, corresponding to cortical synchrony (Ermentrout and Kleinfeld, 2001).

In area V4, saccadic eye movements made in the presence of visual stimulations have been shown to trigger traveling waves (Zanos et al., 2015). They theorized that saccadic suppression (Kleiser et al., 2004) may result from transient activation of local inhibitory circuits; which could then initiate the transition to a wave pattern at the end of the saccade. Similar ideas have been around for a while. Singer (1977) analysed postsynaptic potentials in LGN relay cells during Ponto-geniculo-occipital (PGO) waves, revealing that facilitation was mainly due to the blockade of inhibitory circuits. Specifically, regarding eye movements, the author interprets that the brief phase of disinhibition serves to reset the thalamic relay each time the

point of fixation is changed. Erasing the inhibitory gradient is associated with a release from the adaptation inertia, assuring a bias-free processing after the saccade. Building on these ideas, I propose that there could be a wave caused by an efferent copy of the oculomotor command (Sommer and Wurtz, 2008), which travels from the thalamic relay throughout the cortex, priming the visual system for the post-saccadic stimulus. My interpretation is that the release from pre-saccadic adaptation is one of the consequences of a larger mechanism that includes saccadic suppression and saccadic enhancement (Benedetto and Morrone, 2017).

5.2 Eye Movements Beside the Saccade

Fixation Drift. In addition to the saccade, there are other basic eye movements: smooth pursuit, vergence, and vestibulo-ocular movements (Purves et al., 2001). What is more interesting is that, even during fixation, the eye is never completely motionless (Barlow, 1952). Slow drift movements are common. Boi et al. (2017) suggest that eye movements in the post-saccadic period convert spatial information into temporal modulation on the retina. The fast saccade together with the slow fixation drift dynamically reformat the visual image, which could underlie a system of coarse-to-fine analysis.

Microsaccade. There are perpetual rhythmic eye movements (Bosman et al., 2009), and tiny eye movements may have a big impact on perception. After all, microsaccades (Melloni et al., 2009) are generated from the same system as normal saccades (Hafed et al., 2009), and produce significant perceptual alterations (Hafed, 2013). Hafed and Ignashchenkova (2013) developed a microsaccadic countermanding model. They propose that the presentation of a stimulus initiates a competing motor

command (saccade to stimulus) that interacts with the current command (stay on fixation). It is interesting how this model contrast with the one suggested in this memoir. Whereas I contemplated the idea that saccadic eye movements reorient the dynamics of the visual system, they submitted how visual cues reset oscillatory rhythms of the oculomotor system. Two systems, each resetting the other, it may be that both systems interact creating a harmony of oscillation.

Microsaccades have also been linked causally to covert shift in attention (Hafed et al., 2015) in a fundamental, almost reflexive manner. This suggests that peri-microsaccadic changes can play a significant role in accounting for attentional phenomena. Interestingly, these peri-saccadic modulations are yet again contrasting with our model. Considering that we postulated an increase in sensitivity immediately following the saccade or an optimal temporal processing window. Inversely, microsaccades have been associated with an enhancement prior to the eye movement (Chen et al., 2015). Perhaps these results reveal different levels of processing. The rhythmic oscillations of microsaccades could be a tool for the visual system to generate strong and synchronized onset transients in the visual input stream (Rolfs, 2009), without changing target. Although the benefit of microsaccade may come from a temporal redistribution of the power of an otherwise stationary stimulus (Mostofi et al., 2016).

5.3 Future Directions

Foveal Vision. A crucial development for vision science is the inclusion of the fovea. In comparison with its central role in perception, the fovea receives little attention from the scientific community. It is more complex to set up the experiment,

as the presence of a fixation target is a non-starter. However, the existence of extra-saccadic movement during fixation disputes the traditional experimental paradigm. This challenges the researcher ability to control variables and have a neutral background for the visual stimulus.

Foveal vision also challenges our view of brain areas, as there is a region of the visual cortex where the foveal representations of V1, V2, V3 and V4 converge (Gattass et al., 1988). The segmentation of the brain into distinct processing units and tractable pathways might not be a faithful representation of what is going on inside the brain. It is more likely that brain area participate in multiple overlapping hierarchical computations.

Inhibitory Stimulus. Occasionally, the probe stimulus can act as an inhibitor, suppressing the neuronal firing rate below the baseline acquired in fixation. This happens through lateral inhibition when the probe stimulus falls beside the neuron excitatory receptive field, when the fixation point is the preferred stimulus. Anecdotally, I found some instances where the contrast of the test stimulus was discernible in the level of inhibition (figure 5–1). In comparison, the presentation of the test stimulus during fixation yielded no response. In that case, the benefit of a saccade comes from a synchronized visual transient that enables neurons to encode the feature of a stimulus that falls outside of their classical receptive field. This reiterate that post-saccadic vision transcend what we can study during fixation, in the traditional paradigm of vision research.

Natural Scene. Advancements in neuroscience can benefit from using tasks that are more organic to the animal's behavior (Snow et al., 2017). Natural scenes

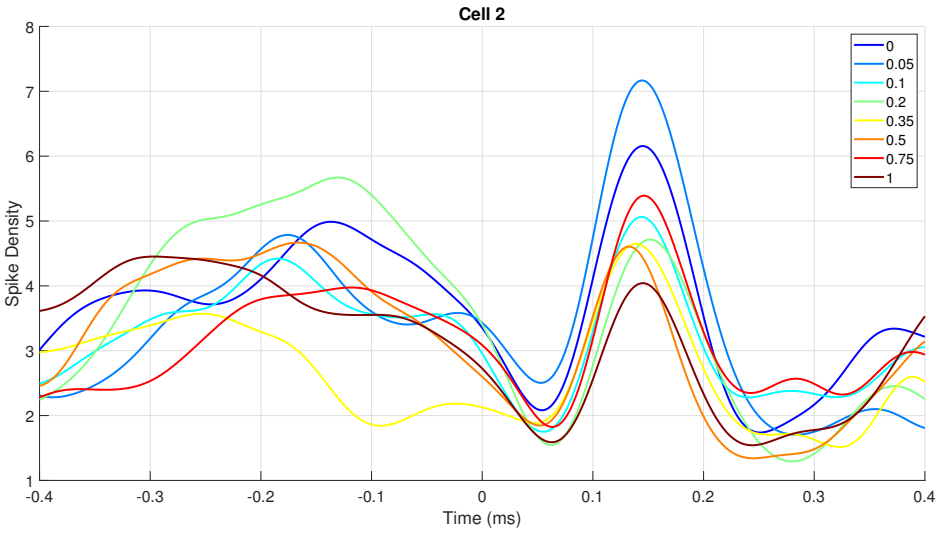


Figure 5–1: **Inhibitory Probe.** Some neurons responded preferentially to the fixation point, more so, the probe stimulus was in the inhibitory receptive field. Although the neurons did not respond to the probe stimuli during fixation, there is a noticeable modulation on the response by the contrast only after the saccade. This illustrate how saccade can benefit the visual system by expanding the classical receptive field.

drive visual neurons in more profound ways (MacEvoy et al., 2008), and eliminate the need to elucidate the optimal stimulus for each neuron. This becomes more important as we move up the hierarchy to higher-order areas. Tweaking the paradigm of simulated saccades, the experiment presented in this thesis could be reproduced in a free viewing task. The animal would be assigned with a visual foraging initiative to find a hidden target in a complex scene. Once the animal has completed the task, we capture the sequence of eye movements and perform a control experiment by having the monkey fixate while we *replay* the trial by moving the image to produce the same retinal stimulation. This method would yield a wide variety of contrasts, temporal dynamics and eye movements that are behaviorally relevant.

5.4 Conclusion

This thesis focused on the interaction between ocular motion and the visual system. Specifically, on the influence of the saccade on the aftereffect of adaptation. I proposed that the saccade must positively modulate the visual activity to erase the trans-saccadic adaptation aftereffect and permit a bias-free viewing on each fixation.

My research met its objective and demonstrated that the oculomotor and visual systems work in close coordination. In chapter 3, I analyzed cortical neurons from awake monkeys performing a simple oculomotor-visual task and I discovered that the presence of an eye movement in between the adapter and probe stimuli diminished the aftereffect of adaptation greatly. However, the improvement from the saccade is temporary as delayed post-saccadic probes are still influenced by the adapter. This signifies that the aftereffect of adaptation is not erased trans-saccadically. Instead,

active modulation from the oculomotor system transiently sets the visual system in a condition that permits impartial processing of the post-saccadic stimulus.

In chapter 4, I showed that adaptation can emerge from attractor dynamics. I established that the saccade modulates the neuronal trajectory to a more favorable state. My results illustrated the importance of the neuronal history leading to the probe presentation. Instead of saying that the saccade releases the effect of adaptation, I suggest that the saccade actively drives the neuronal manifold toward a state that is propitious to the optimal processing of subsequent stimuli.

Together with the theoretical implications discussed in chapter 5, my findings suggest that eye movements have an important role beyond a simple foraging initiative. Saccades have a dynamic involvement in visual perception. The visual system may function in two distinct activation phases. The first phase, driven by the saccade and the synchronized visual onset, triggers a bottom-up cascade through the visual hierarchy. The second phase is dominated by top-down large scale recurrent connections.

Classical studies emphasize the rate of response to visual stimulation. However, it is becoming clear that comprehension of the visual system mandate more attention to the timing of neuronal activity, not only to the visual stimulus but also with respect to ocular motion. A holistic picture emerges of the visual system, the oculomotor system and the attention system pulsating collaboratively in a dance of oscillation.

REFERENCES

Abbott, L. F., Varela, J., Sen, K. and Nelson, S. (1997) Synaptic depression and cortical gain control. *Science*, **275**, 221–224.

Albrecht, D. G., Geisler, W. S. and Crane, A. M. (2003) Nonlinear properties of visual cortex neurons: Temporal dynamics, stimulus selectivity, neural performance. *The visual neurosciences*, **1**, 747–764.

Asaad, W. F., Santhanam, N., McClellan, S. and Freedman, D. J. (2012) High-performance execution of psychophysical tasks with complex visual stimuli in matlab. *Journal of neurophysiology*, **109**, 249–260.

Barlow, H. (1990) A theory about the functional role and synaptic mechanism of visual after-effects. *Vision: Coding and efficiency*, **363375**.

Barlow, H. B. (1952) Eye movements during fixation. *The Journal of Physiology*, **116**, 290–306.

Benedetto, A. and Morrone, M. C. (2017) Saccadic suppression is embedded within extended oscillatory modulation of sensitivity. *Journal of Neuroscience*, **37**, 3661–3670.

Boi, M., Poletti, M., Victor, J. D. and Rucci, M. (2017) Consequences of the oculomotor cycle for the dynamics of perception. *Current Biology*, **27**, 1268–1277.

Bosman, C. A., Womelsdorf, T., Desimone, R. and Fries, P. (2009) A microsaccadic rhythm modulates gamma-band synchronization and behavior. *Journal of*

Neuroscience, **29**, 9471–9480.

Boussaoud, D., Desimone, R. and Ungerleider, L. G. (1991) Visual topography of area teo in the macaque. *Journal of comparative neurology*, **306**, 554–575.

Campbell, F. W. and Wurtz, R. H. (1978) Saccadic omission: why we do not see a grey-out during a saccadic eye movement. *Vision research*, **18**, 1297–1303.

Carandini, M. and Heeger, D. J. (2012) Normalization as a canonical neural computation. *Nature Reviews Neuroscience*, **13**, 51.

Cavanagh, P., Hunt, A. R., Afraz, A. and Rolfs, M. (2010) Visual stability based on remapping of attention pointers. *Trends in cognitive sciences*, **14**, 147–153.

Cavanaugh, J. R., Bair, W. and Movshon, J. A. (2002) Nature and interaction of signals from the receptive field center and surround in macaque v1 neurons. *Journal of neurophysiology*, **88**, 2530–2546.

Chaure, F. J., Rey, H. G. and Quian Quiroga, R. (2018) A novel and fully automatic spike-sorting implementation with variable number of features. *Journal of neurophysiology*, **120**, 1859–1871.

Chen, C.-Y., Ignashchenkova, A., Thier, P. and Hafed, Z. M. (2015) Neuronal response gain enhancement prior to microsaccades. *Current Biology*, **25**, 2065–2074.

De Pisapia, N., Kaunitz, L. and Melcher, D. (2010) Backward masking and unmasking across saccadic eye movements. *Current Biology*, **20**, 613–617.

Dennis Jr, J. E. (1977) Nonlinear least squares. *State of the art in numerical analysis*, 269–312.

Diamond, M. R., Ross, J. and Morrone, M. C. (2000) Extraretinal control of saccadic suppression. *Journal of Neuroscience*, **20**, 3449–3455.

DiCarlo, J. J. and Cox, D. D. (2007) Untangling invariant object recognition. *Trends in cognitive sciences*, **11**, 333–341.

DiCarlo, J. J., Zoccolan, D. and Rust, N. C. (2012) How does the brain solve visual object recognition? *Neuron*, **73**, 415–434.

E. Irwin Robert D. Gordon, D. (1998) Eye movements, attention and trans-saccadic memory. *Visual cognition*, **5**, 127–155.

Ermentrout, G. B. and Kleinfeld, D. (2001) Traveling electrical waves in cortex: insights from phase dynamics and speculation on a computational role. *Neuron*, **29**, 33–44.

Felleman, D. J. and Van, D. E. (1991) Distributed hierarchical processing in the primate cerebral cortex. *Cerebral cortex (New York, NY: 1991)*, **1**, 1–47.

Frazor, R. A. and Geisler, W. S. (2006) Local luminance and contrast in natural images. *Vision research*, **46**, 1585–1598.

Gattass, R., Sousa, A. and Gross, C. (1988) Visuotopic organization and extent of v3 and v4 of the macaque. *Journal of Neuroscience*, **8**, 1831–1845.

Gawne, T. J. and Woods, J. M. (2003) The responses of visual cortical neurons encode differences across saccades. *Neuroreport*, **14**, 105–109.

Gerstner, W., Kistler, W. M., Naud, R. and Paninski, L. (2014) *Memory and attractor dynamics*, 442466. Cambridge University Press.

Goldberg, M. E., Bisley, J., Powell, K. D., Gottlieb, J. and Kusunoki, M. (2002) The role of the lateral intraparietal area of the monkey in the generation of saccades and visuospatial attention. *Annals of the New York Academy of Sciences*, **956**, 205–215.

Greenlee, M. W. and Kimmig, H. (2019) Visual perception and eye movements. *Eye Movement Research: An Introduction to its Scientific Foundations and Applications*, 165.

Guez, J. S. (2015) *Neural mechanisms and functional signficance of peri-saccadic response modulation*. Ph.D. thesis, Rutgers University-Graduate School-Newark.

Hafed, Z. M. (2013) Alteration of visual perception prior to microsaccades. *Neuron*, **77**, 775–786.

Hafed, Z. M., Chen, C.-Y. and Tian, X. (2015) Vision, perception, and attention through the lens of microsaccades: mechanisms and implications. *Frontiers in systems neuroscience*, **9**, 167.

Hafed, Z. M., Goffart, L. and Krauzlis, R. J. (2009) A neural mechanism for microsaccade generation in the primate superior colliculus. *science*, **323**, 940–943.

Hafed, Z. M. and Ignashchenkova, A. (2013) On the dissociation between microsaccade rate and direction after peripheral cues: microsaccadic inhibition revisited. *Journal of Neuroscience*, **33**, 16220–16235.

Hegde, J. and Felleman, D. J. (2007) Reappraising the functional implications of the primate visual anatomical hierarchy. *The Neuroscientist*, **13**, 416–421.

Hegdé, J. and Van Essen, D. C. (2007) A comparative study of shape representation in macaque visual areas v2 and v4. *Cerebral Cortex*, **17**, 1100–1116.

Heitmann, S., Gong, P. and Breakspear, M. (2012) A computational role for bistability and traveling waves in motor cortex. *Frontiers in computational neuroscience*, **6**, 67.

Henderson, J. M. and Hollingworth, A. (1998) Eye movements during scene viewing: An overview. In *Eye guidance in reading and scene perception*, 269–293. Elsevier.

Hochstein, S. and Ahissar, M. (2002) View from the top: Hierarchies and reverse hierarchies in the visual system. *Neuron*, **36**, 791–804.

Hubel, D. and Wiesel, T. (1960) Receptive fields of optic nerve fibres in the spider monkey. *The Journal of physiology*, **154**, 572–580.

Hubel, D. H. and Wiesel, T. N. (1962) Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *The Journal of physiology*, **160**, 106–154.

Ibbotson, M. and Krekelberg, B. (2011) Visual perception and saccadic eye movements. *Current opinion in neurobiology*, **21**, 553–558.

Ibbotson, M. R., Price, N. S., Crowder, N. A., Ono, S. and Mustari, M. J. (2007) Enhanced motion sensitivity follows saccadic suppression in the superior temporal sulcus of the macaque cortex. *Cerebral cortex*, **17**, 1129–1138.

Javal, E. (1878) Essai sur la physiologie de la lecture. *Annales d'Ocilistique*, **80**, 97–117.

JR Duhamel, Colby, C. and Goldberg, M. (1992) The updating of the representation of visual space in parietal cortex by intended eye movements. *Science*, **255**, 90–92.

Kaliukhovich, D. A. and Vogels, R. (2016) Divisive normalization predicts adaptation-induced response changes in macaque inferior temporal cortex. *Journal of Neuroscience*, **36**, 6116–6128.

Kleiser, R., Seitz, R. J. and Krekelberg, B. (2004) Neural correlates of saccadic suppression in humans. *Current Biology*, **14**, 386–390.

Knöll, J., Binda, P., Morrone, M. C. and Bremmer, F. (2011) Spatiotemporal profile of peri-saccadic contrast sensitivity. *Journal of vision*, **11**, 15–15.

Kohn, A. (2007) Visual adaptation: physiology, mechanisms, and functional benefits. *Journal of neurophysiology*, **97**, 3155–3164.

Krizhevsky, A., Sutskever, I. and Hinton, G. E. (2012) Imagenet classification with deep convolutional neural networks. In *Advances in neural information processing systems*, 1097–1105.

Lakatos, P., Chen, C.-M., O'Connell, M. N., Mills, A. and Schroeder, C. E. (2007) Neuronal oscillations and multisensory interaction in primary auditory cortex. *Neuron*, **53**, 279–292.

LeCun, Y., Bottou, L., Bengio, Y. and Haffner, P. (1998) Gradient-based learning applied to document recognition. *Proceedings of the IEEE*, **86**, 2278–2324.

Li, P., Zhu, S., Chen, M., Han, C., Xu, H., Hu, J., Fang, Y. and Lu, H. D. (2013) A motion direction preference map in monkey v4. *Neuron*, **78**, 376–388.

MacEvoy, S. P., Hanks, T. D. and Paradiso, M. A. (2008) Macaque v1 activity during natural vision: effects of natural scenes and saccades. *Journal of neurophysiology*, **99**, 460–472.

Maldonado, P., Babul, C., Singer, W., Rodriguez, E., Berger, D. and Grun, S. (2008) Synchronization of neuronal responses in primary visual cortex of monkeys viewing natural images. *Journal of neurophysiology*, **100**, 1523–1532.

Mante, V., Sussillo, D., Shenoy, K. V. and Newsome, W. T. (2013) Context-dependent computation by recurrent dynamics in prefrontal cortex. *nature*, **503**, 78.

del Mar Quiroga, M., Morris, A. P. and Krekelberg, B. (2016) Adaptation without plasticity. *Cell reports*, **17**, 58–68.

Marr, D. (1982) *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information*. New York, NY, USA: Henry Holt and Co., Inc.

Massey Jr, F. J. (1951) The kolmogorov-smirnov test for goodness of fit. *Journal of the American statistical Association*, **46**, 68–78.

Matin, E., Clymer, A. B. and Matin, L. (1972) Metacontrast and saccadic suppression. *Science*, **178**, 179–182.

Melloni, L., Schwiedrzik, C. M., Rodriguez, E. and Singer, W. (2009) (micro) saccades, corollary activity and cortical oscillations. *Trends in cognitive sciences*, **13**, 239–245.

Mostofi, N., Boi, M. and Rucci, M. (2016) Are the visual transients from microsaccades helpful? measuring the influences of small saccades on contrast sensitivity. *Vision research*, **118**, 60–69.

Najemnik, J. and Geisler, W. S. (2005) Optimal eye movement strategies in visual search. *Nature*, **434**, 387–391.

Neupane, S., Guitton, D. and Pack, C. C. (2016) Two distinct types of remapping in primate cortical area v4. *Nature communications*, **7**, 10402.

— (2017) Coherent alpha oscillations link current and future receptive fields during saccades. *Proceedings of the National Academy of Sciences*, **114**, E5979–E5985.

O'Reilly, R. C., Wyatte, D., Herd, S., Mingus, B. and Jilk, D. J. (2013) Recurrent processing during object recognition. *Frontiers in psychology*, **4**, 124.

Paradiso, M. A., Meshi, D., Pisarcik, J. and Levine, S. (2012) Eye movements reset visual perception. *Journal of vision*, **12**, 11–11.

Patterson, C. A., Duijnhouwer, J., Wissig, S. C., Krekelberg, B. and Kohn, A. (2014) Similar adaptation effects in primary visual cortex and area mt of the macaque monkey under matched stimulus conditions. *Journal of neurophysiology*, **111**, 1203–1213.

Patterson, C. A., Wissig, S. C. and Kohn, A. (2013) Distinct effects of brief and prolonged adaptation on orientation tuning in primary visual cortex. *Journal of Neuroscience*, **33**, 532–543.

Peirce, J. W. (2007) The potential importance of saturating and supersaturating contrast response functions in visual cortex. *Journal of vision*, **7**, 13–13.

Purves, D., Augustine, G. J., Fitzpatrick, D., Katz, L. C., LaMantia, A.-S., McNamara, J. O., Williams, S. M. et al. (2001) Types of eye movements and their functions. *Neuroscience*, 361–390.

Rajkai, C., Lakatos, P., Chen, C.-M., Pincze, Z., Karmos, G. and Schroeder, C. E. (2007) Transient cortical excitation at the onset of visual fixation. *Cerebral Cortex*, **18**, 200–209.

Reppas, J. B., Usrey, W. M. and Reid, R. C. (2002) Saccadic eye movements modulate visual responses in the lateral geniculate nucleus. *Neuron*, **35**, 961–974.

Rieke, F. and Rudd, M. E. (2009) The challenges natural images pose for visual adaptation. *Neuron*, **64**, 605–616.

Riesenhuber, M. and Poggio, T. (1999) Hierarchical models of object recognition in cortex. *Nature neuroscience*, **2**, 1019–1025.

Rochon-Duvigneaud, A. (1907) Recherches sur la fovea de la rétine humaine et particulièrement sur le bouquet des cônes centraux. *Arch Anat Microsc*, **11**, 315–342.

Roe, A. W., Chelazzi, L., Connor, C. E., Conway, B. R., Fujita, I., Gallant, J. L., Lu, H. and Vanduffel, W. (2012) Toward a unified theory of visual area v4. *Neuron*, **74**, 12–29.

Rolfs, M. (2009) Microsaccades: small steps on a long way. *Vision research*, **49**, 2415–2441.

Ross, J. and Ma-Wyatt, A. (2004) Saccades actively maintain perceptual continuity. *Nature Neuroscience*, **7**, 65.

Sani, I., Santandrea, E., Golzar, A., Morrone, M. C. and Chelazzi, L. (2013) Selective tuning for contrast in macaque area v4. *Journal of Neuroscience*, **33**, 18583–18596.

Sclar, G., Lennie, P. and DePriest, D. D. (1989) Contrast adaptation in striate cortex of macaque. *Vision research*, **29**, 747–755.

Serre, T. (2013) *Hierarchical Models of the Visual System*, 1–12. New York, NY: Springer New York.

Shapley, R. and Enroth-Cugell, C. (1984) Visual adaptation and retinal gain controls. *Progress in retinal research*, **3**, 263–346.

Sharpee, T. O., Sugihara, H., Kurgansky, A. V., Rebrik, S. P., Stryker, M. P. and Miller, K. D. (2006) Adaptive filtering enhances information transmission in visual cortex. *Nature*, **439**, 936–942.

Sherman, S. M. and Guillery, R. W. (2006) *Exploring the thalamus and its role in cortical function*. MIT press.

Singer, W. (1977) Control of thalamic transmission by corticofugal and ascending reticular pathways in the visual system. *Physiological reviews*, **57**, 386–420.

Snow, M., Coen-Cagli, R. and Schwartz, O. (2017) Adaptation in the visual cortex: a case for probing neuronal populations with natural stimuli. *F1000Research*, **6**.

Solomon, S. G. and Kohn, A. (2014) Moving sensory adaptation beyond suppressive effects in single neurons. *Current Biology*, **24**, R1012–R1022.

Sommer, M. A. and Wurtz, R. H. (2008) Visual perception and corollary discharge. *Perception*, **37**, 408–418.

Stevens, K. A. (2012) The vision of david marr. *Perception*, **41**, 1061–1072.

Tanigawa, H., Lu, H. D. and Roe, A. W. (2010) Functional organization for color and orientation in macaque v4. *Nature neuroscience*, **13**, 1542.

Vinken, K., Boix, X. and Kreiman, G. (2019) Incorporating neuronal fatigue in deep neural networks captures dynamics of adaptation in neurophysiology and perception. *bioRxiv*, 642777.

Wainwright, M., Schwartz, O. and Simoncelli, E. (2002) *Natural image statistics and divisive normalization: Modeling nonlinearity and adaptation in cortical neurons*, 203–222. MIT Press.

Wark, B., Lundstrom, B. N. and Fairhall, A. (2007) Sensory adaptation. *Current opinion in neurobiology*, **17**, 423–429.

Whitmire, C. J. and Stanley, G. B. (2016) Rapid sensory adaptation redux: a circuit perspective. *Neuron*, **92**, 298–315.

Wurtz, R. H. (2008) Neuronal mechanisms of visual stability. *Vision research*, **48**, 2070–2089.

Zanos, T. P., Mineault, P. J., Guitton, D. and Pack, C. C. (2016) Mechanisms of saccadic suppression in primate cortical area v4. *Journal of Neuroscience*, **36**, 9227–9239.

Zanos, T. P., Mineault, P. J., Nasiotis, K. T., Guitton, D. and Pack, C. C. (2015) A sensorimotor role for traveling waves in primate visual cortex. *Neuron*, **85**, 615–627.

Zirnsak, M., Steinmetz, N. A., Noudoost, B., Xu, K. Z. and Moore, T. (2014) Visual space is compressed in prefrontal cortex before eye movements. *Nature*, **507**, 504.