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Focus on fixations

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Chapter 1

Introduction

Eye movements are essential to human visual perception. Vision may be the most important sense for functioning in our daily life, evident from the fact that a large portion of our brain is dedicated to the processing of the information coming from our eyes and controlling the movements of our eyes. Human vision is only crisp at the center of gaze and visual acuity rapidly decreases in the periphery of the visual field. Therefore, we need to actively move our eyes to change our focus when we want to scrutinize different scene elements.

Over the recent years, research studying the neural basis of visual perception has embraced the use of functional Magnetic Resonance Imaging (fMRI). For various reasons, eye movements, in spite of their obvious importance to visual perception, have scarcely been considered in fMRI research to date. This thesis attempts to make up arrears by studying the intricate link between eye movements and human visual perception using fMRI. Foremost, it aims to answer the following question:

How does the human brain process visual information in relation to eye movements?

This question encompasses two subsidiary questions that are concerned with 1) how the visual brain determines what parts of the scene are important for inspection, and 2) how it processes the visual information that is acquired during natural viewing behaviour? Before these questions can be answered, a more technical question must be answered as well: Can eye-movements be used in the analysis of fMRI data? In a series of experiments, this thesis contributes to answering these questions.

After detailing the aim and scope of the thesis (*section 1.1*), and listing the general conclusions of this thesis (*section 1.2*), the remainder of this introductory chapter will summarize the foundations of human visual neuroscience relevant to the topic of this thesis. First, the layout of our visual system is briefly explained (*section 1.3*). This is followed by a section on human viewing behaviour (*section 1.4*). Finally, *section 1.5* introduces the methods to study cortical processing during natural viewing.

1.1 Aims, scope and layout of this thesis

This thesis concerns the intricate link between eye movements and human visual perception. Foremost, it aims to answer the following question:

How does the human brain process visual information in relation to eye movements?

This question encompasses three subsidiary questions. This thesis contributes to answering these questions in a series of experiments.

The first subsidiary question is *'How does the visual brain determine what parts of the scene are important to redirect our gaze at?'* It is addressed in the following chapters (*Chapters 2 – 5*).

Chapter 2 describes an experiment aimed at predicting to what extent stimulus features determine where people direct their gaze. We show how features of inspected patches from natural images differ from non-inspected ones, and show how these features can be used to predict where people look.

Chapter 3 In Chapter 3, we determine where color information is processed in the visual brain. This study explores the use of multivariate pattern analysis methods in brain research.

Chapter 4 These multivariate methods are used in Chapter 4 to show that eye fixations are meaningful events that can be used to study visual perception using fMRI research. This resulted in a novel technique that we call fixation based event-related (FIBER) fMRI. FIBER-fMRI allows incorporating natural viewing behaviour in fMRI paradigms.

Chapter 5 In Chapter 5, we use the new FIBER-fMRI approach to study the neural correlates of priority, a recently suggested construct that integrates top-down context-based relevance and bottom-up stimulus-driven saliency. In Chapter 5, we propose a new measure to calculate priority based on eye movements, show that it is different from current image-based measures of saliency, surprise and motion, and find that priority is represented in select cortical areas.

The second – and more technical – subsidiary question is: *"Can fixations be used as meaningful events in fMRI analysis?"* Fundamental proof that this is the case is provided by Chapter 4. Additionally, In Chapters 5 and 6 fixations show added value in the search for neural correlates of visual processing during natural viewing.

The third subsidiary question of this thesis is: *Where is the visual information processed that is acquired during natural viewing behaviour?*

Chapter 6 describes an experiment that provides a first answer to this question. By applying FIBER-fMRI, we show that visual information processing in various cortical regions has a different dependence on viewing behaviour.

1.2 General conclusions

The majority of the work described in this thesis examines visual information processing in relation to eye movements when humans are engaged in natural viewing behaviour. From these studies I conclude that including eye movement behaviour in fMRI designs has the potential to significantly enhance the study into the neural correlates of human visual perception.

This conclusion is based on a number of findings. First, we found that visual information at the location of fixations is different from that at random scene locations (*Chapter 2*). Second, fixations – despite their sub-optimal properties for evoking fMRI responses – can be used to extract meaningful responses in targeted brain regions using fMRI (*Chapter 4*). Moreover, the fMRI responses in such regions contain information about the type of object people fixated. In other words, based on brain activity recorded using fMRI during dynamic viewing, it is possible to determine what aspects of a stimulus drive people's gaze (*Chapter 4*). Third, this thesis provides the first evidence for a “priority” mechanism in humans that identifies – based on the combination of stimulus saliency and task relevance – the aspects of a scene that the observer should gaze at (*Chapter 5*). Fourth and final, work in this thesis indicates that brain activity in medial and lateral regions in ventral visual cortex is associated with the type of viewing behaviour that is performed by the observer (*Chapter 6*).

Hence, this thesis contributes to our understanding of how visual information is processed in the brain in relation to eye movements by: 1) showing that both brain responses and stimulus features can be used to predict where people direct their gaze; 2) providing a novel analysis method which allows incorporating natural viewing behaviour in fMRI research; 3) implementing an original approach for measuring priority and determining its neural correlates 4) indicating that viewing behaviour differently affects activity in select parts of the ventral visual cortex.

1.3 The human visual system

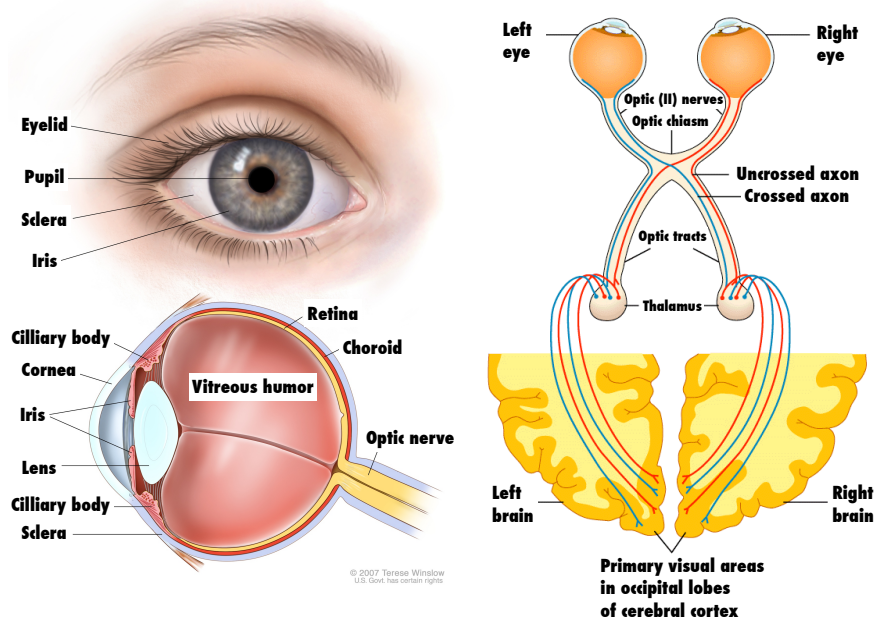


Figure 1.1: The visual system. Adapted from: <http://www.cancer.gov>, <http://www.wikipedia.org>

Our visual system comprises a number of complex structures, each having their specific function. Figure 1.1 displays all major structures of the visual system. The incoming light first passes the pupil and is projected on the retina (left bottom part of figure 1.1). Light sensitive cells in the retina, called receptors, are specialized for light perception at either low luminance (rods) or at high luminance (cones) and convert the light signal into a neural signal. The human retina contains three different types of cones that each have their maximum sensitivity in a different part of the visible spectrum. Because of this, the cone signals provide the basis for human color vision.

The retina contains a number of additional layers of cells, which also perform the first processing on the neural signal. Specialized ganglion cells exist that relay specific aspects of the visual information to the brain. The main classes of retinal ganglion cells are Magnocellular (M), Parvocellular (P) and Koniocellular (K) cells. M-cells combine the information from the three different cones, and mainly processes luminance and contrast information. M-cell signals are used in the processing of movement and are highly sensitive to differences in brightness. P-cells process color signals from the cones in the retina. To date, the precise function of the K-cells remains unclear, but they may also be involved in color processing. From the retina, the neural signals are relayed via the optic nerve, optic chiasm, Lateral Geniculate Nucleus (LGN), and the optic radiations to the primary visual cortex (V₁) in the occipital pole of the cerebral cortex (see figure 1.1, right). V₁ deals with low level processing of visual input (e.g., orientation or color). Furthermore, V₁ has a retinotopic organization. Retinotopy entails the projection of the visual input where adjacent points in the visual field correspond to adjacent points on the cortex.

From V1 onward, neural signals are relayed to many different cortical and subcortical structures. The subsequent processing of visual information is organized into two major processing pathways.

These two pathways relay information from visual cortex towards the rest of the brain. After their discovery in 1967 by Trevarthen in frogs and in fish by Ingle, a large body of literature has corroborated the existence of these pathways in both mammals and humans^{20,21,22,29}. Each pathway serves a different function in visual information processing.

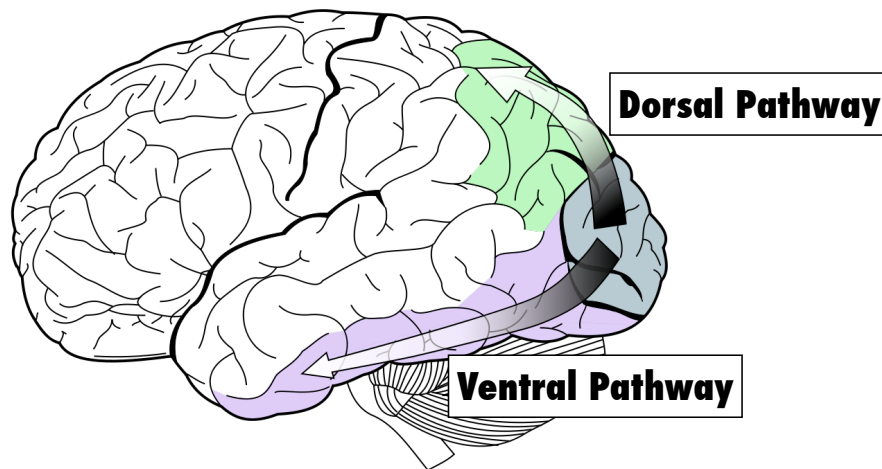


Figure 1.2: Two visual pathways each enabling different visual functions: Perception for action in the dorsal stream (green); Perception for recognition in the ventral stream (purple). Source: <http://www.wikipedia.org>

The dorsal pathway (the “where” pathway) enables perception for action, and runs from the occipital pole towards the parietal lobe. The dorsal route primarily processes information from the magnocellular ganglion cells. Information in the dorsal route has been shown to contribute to visuospatial functions (e.g., grasping, shifting attention or reaching). Chapter 5 reports that regions in the dorsal stream contribute to the processing of visuospatial attention in natural human viewing behaviour.

The ventral pathway (the “what” pathway) enables perception for recognition, and runs from the occipital pole towards temporal lobes. The ventral pathway is thought to process primarily input from the parvocellular cells. This pathway deals with visual processing for conscious perception of objects and the ability to recognize and identify them. In contrast, ventral regions have also been identified to rapidly extract the ‘gist’ of a scene. Chapter 6 examines how both types of visual perception are combined in the ventral visual system for natural human viewing behaviour.

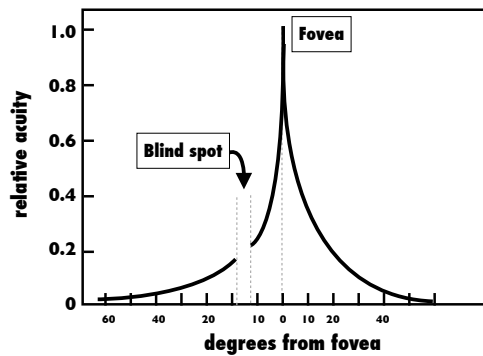


Figure 1.3: Distribution of relative visual acuity across the retina. Recreated after Core et al.⁹

1.4 Viewing behaviour

Human vision is only crisp at the center of gaze and visual acuity rapidly decreases in the periphery of the visual field (see figure 1.3). Therefore, we need to actively move our eyes to change our focus when we want to scrutinize different scene elements. During everyday behaviour, we move our eyes 3-5 times per second¹⁶. Eye movements can be categorized in a number of different behaviours:

Fixations During a fixation, gaze is maintained on a single location. In general a fixation can last between approximately 100 - 2000 ms and on average lasts 300 ms.

Saccades Rapid movements of the eye to redirect our gaze.

Smooth pursuit eye movements During a smooth pursuit eye movement, the eye closely follows a moving object.

The essential role of eye movements in visual perception has been repeatedly demonstrated^{12,14,18}. When the retinal image is stabilized, vision quickly degrades due to adaptation -the decreased responsiveness to a constantly present stimulus. Eye-movements are necessary to restore vision¹⁸. But also many tasks require that we continuously shift our gaze to acquire information from different aspects of the environment. The change of gaze results in novel samples of the environment, each time projected differently on the retina. This sampling of information from the environment requires that visual perception is investigated within the framework of active vision^{10,12,14,16}. The work in this thesis contributes to the investigation of active vision using fMRI.

I. Recording of eye movements

Most of the experiments described in this thesis use eye tracking as one of its core methods to investigate human visual behaviour. Mainly three types of eye trackers exist: 1) sensor-based eye trackers, where a magnetic sensor embedded to a contact lens is placed on the eye. 2) Electro-oculography (EOG), which uses electrodes placed around the eyes to register eye position. 3) Video-based eye tracking, where the image of the eye is captured using a camera. Because video-based eye tracking is non-invasive, it is often preferred and most widely used in research as well as commercial applications.

In its essence, video based eye trackers comprise a camera unit with illumination. Today's eye tracking systems use an infrared (IR) illumination produced via light-emitting diodes (LEDs). There are two reasons for this type of lighting in eye tracking systems: First, the use of a light source in the scene enhances the quality of the image in terms of contrast and intensity levels, and it facilitates detailed image analysis and gaze estimation. Second, IR optical radiation is invisible to the human eye, so that the lighting is comfortable and does not distract user's attention. The camera unit retains both high temporal and spatial resolution. A close-up video image of the eye

is sent to a computer, on which a dedicated image processing algorithm extracts the pupil and the bright reflection of the cornea to determine its position and subsequently stores the positions to a file. Prior calibration of the eye tracking system is necessary to map the eye position onto screen coordinates. This is achieved by recording the position of the pupil together with the position of the reflection of the cornea for a number of fixed points on the screen.

After an experiment has ended, the researcher is left with a list of screen coordinates and their corresponding time stamps. However, eye movements events of human viewing behaviour are fixations, saccades and blinks. Event detection is used to classify recorded gaze points into periods of fixation, saccade, smooth pursuit, blink, and noise. These algorithms primarily focus on either fixations or saccades²⁵. Fixation Detection algorithms assess whether dwell time on certain locations with minimal dispersion exceeds a certain threshold. If this is the case, a fixation is detected. Saccade detection algorithms are driven by the increase in the eye's velocity to determine saccades.

The resources available for visual perception are limited and make a selection mechanism necessary. Selection is achieved by moving our eyes and shifting of attention to those parts of the scene that are potentially interesting or important. What determines whether something in a scene is worth looking at? Often, our gaze appears to be drawn automatically toward highly distinct elements of a scene. These scene elements stand out based on their stimulus features relative to the rest of the scene and are "salient". For instance, a single red poppy in a pasture of green grass draws our gaze based on its color contrast. However, such saliency effects can not account for all eye movements we make. For instance, when the task is to look for something green (like a cricket), an inclination to inspect high-contrast objects would not be very helpful. Hence, both image properties and task relevance should influence human viewing behaviour. In chapter 2, image properties based on natural image statistics

are considered for their potential role in guiding human viewing behaviour.

Studies from Buswell in 1935 and from Yarbus in 1967 were the first to consider the importance of task in guiding our eyes^{6,32}. Both researchers primarily instructed observers to look at paintings and varied task instructions. These studies revealed that presenting the same image with various instructions significantly affects the landing points of the saccades. For instance, when the age of the people in the image had to be estimated, faces were much often targeted by the gaze than if the wealth of the depicted family had to be estimated³². The findings of Yarbus and Buswell have since been corroborated in a large number of studies^{1,14,16,16,23,24,28,30}. Chapter 5 introduces a measure for priority – the combination of stimulus salience and task relevance^{4,11} – based on eye movement behaviour and shows where priority might be represented in the human brain. Along a different line, studies have suggested that also different modes of viewing behaviour exist, that may be related to the existence of two different visual pathways^{29,30,31}. In chapter 6, such viewing modes and their neural underpinnings are examined.

1.5 Methods to study cortical processing during natural viewing

II. Recording of brain activity

An array of medical imaging techniques exist which are able to record brain activity. Most common methods are Electroencephalography (EEG), Magnetoencephalography (MEG), functional Magnetic Resonance Imaging (fMRI) and Positron Emission Tomography (PET). Each method has its advantages and disadvantages. fMRI and PET measure local changes in brain hemodynamics and/or flow changes induced by cognitive or perceptual tasks. These measures

have a uniformly high spatial resolution of millimeters or less, but poor temporal resolution. Conversely, EEG and MEG measure the current flows induced by synaptic activity, nearly instantaneously, but the accurate localization of these current flows based on EEG and MEG data alone remains an unsolved problem. These measures have a low spatial resolution and high temporal resolution.

Since the arrival of brain imaging techniques (see Box II), research has been conducted to study the neural correlates of visual perception in natural conditions and with natural viewing. Bartels and Zeki were amongst the first to study natural viewing using fMRI². They presented a James Bond movie and correlated the presence of faces, colors, human bodies and language with brain activity. Activity was found in distinct regions in visual cortex that corresponded to the regions known to process these specific aspects. This suggested that despite the difference in time scale between the BOLD response and the usual fast pace of a movie, the functional specialization of cortex is preserved².

III. Physical principles of fMRI

Generally, Magnetic Resonance Imaging (MRI) works by the fact that (hydrogen) atoms have an angular momentum. After the application of a static magnetic field (the B_0 -field), the magnetic moments (spins) align either parallel or anti-parallel to this field. To obtain a signal, a radio frequency (RF) pulse is applied (see the figure in this box). This results in atoms aligning orthogonal (transversal plane) to the static field, while in the transversal plane a signal can be observed and reconstructed to a three dimensional grid. Cells within this grid are referred to as volume elements (voxels). After the RF pulse, atoms slowly relax to their original alignment and the signal fades out.

Functional MRI entails the measurement of this signal influenced by local inhomogeneities (T_2^*). Active neurons consume oxygen. Due to this oxy-

gen consumption, the level of oxygenated blood decreases in a vessel. A wash-in effect of oxygenated blood takes place and will overcompensate for this low oxygen level, i.e. oxygenation levels increase. This process is slow and on average peaks around three to six seconds after neuronal activation. This is referred to as the Blood Oxygenation Level. Dependent (BOLD) response.

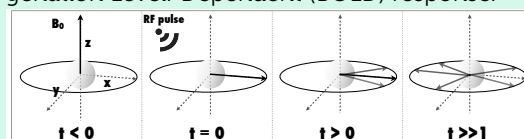


Figure A: T_2^* relaxation. Initial alignment of the net magnetic moment of hydrogen at $t < 0$. After a radio pulse has been sent at $t = 0$, the hydrogen atoms align to the transverse plane (x-y plane), and subsequently starts to dephase over time ($t > 0$ and $t \gg 0$)

IV. The BOLD response

The BOLD response reflects a complex mixture of changes in blood flow, blood volume and metabolic rate of oxygen in cerebral cortex⁷. To simplify fMRI analysis, the BOLD response is assumed to be a constant function throughout the entire cortex. In its simplest form, it can be described using a mixture of two gamma functions (see figure B)⁵. After a pulse of neural activity, the BOLD response peaks around 5 seconds and returns to baseline after 20 seconds approximately.

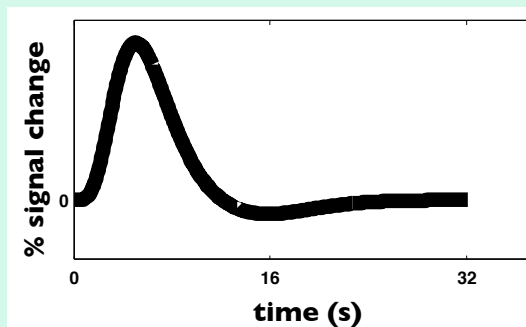


Figure B: Typical BOLD response following a pulse of neural activation. A number of studies have been conducted to investigate brain dynamics for natural viewing.

Novel methods of analysis were required and have been applied to study neural correlates of perception during natural viewing behaviour. In multivariate pattern analysis (see Box V), the interac-

tion between voxels is considered rather than dynamics of individual voxels²⁶. A typical example study showed that brain activity could be distinguished when observers were watching a movie inside an fMRI scanner. When the actor's faces were visible in the movie, this resulted in a different pattern of brain activity compared to when the movie contained scenes of an empty desert¹³. Such brain activity patterns can be used to discern and classify different cognitive states.

V. Multi-Variate Pattern Analysis

The layout of multivariate pattern analysis is somewhat different compared to the layout of univariate General Linear Model (GLM) analysis. In multivariate analyses, a classification problem is addressed: If it is possible to classify between condition A (red circles in figure C) and B (blue squares in figure C), there is a common difference in patterns between examples A and B. Examples are built to represent either condition A or condition B. Subsequently, the total set of examples is divided into two sets: A training set, which is used to train a learning algorithm (e.g., a support vector machine) and a testing set, which is used to validate this learned classification. Performance is determined, by the percentage of correctly classified items of the testing set. For more information, see e.g., Haynes and Rees (2006)¹⁵.

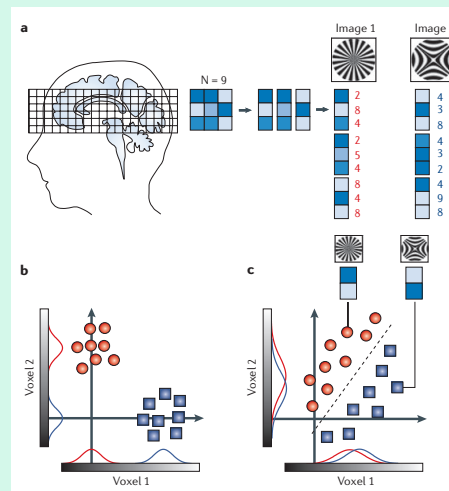


Figure C: Graphical explanation of multivariate pattern analysis, adapted from: Haynes and Rees (2006). Figure a) shows a configuration of a series of voxels, which is reshaped into a vector, losing its topographical meaning. Images b) and c) depict the simplest case, when the vector only contains two voxels.

In another new method, called independent component analysis (ICA) (see Box VI), the fMRI signal is considered as a mixed signal from which sources, i.e., brain networks involved in similar tasks, can be extracted. This method has shown to be very useful when investigating natural viewing behaviour. An important reason for this is that ICA does not rely on the definition of events and analyses the fMRI signal as a whole in order to find clusters of brain regions that show a unique activation profile^{3,17}.

This thesis contributes an additional analysis approach to enable the use of natural viewing in fMRI experiments. Chapter 4 employs multivariate pattern analysis to show that fixations can be used as events in fMRI analysis. The method described in Chapter 4 is referred to as fixation based event-related fMRI (FIBER-fMRI). This method is subsequently used in chapter 5 and 6. Chapter 6 combines FIBER-fMRI with ICA to study specific aspects of natural viewing behaviour.

VI. Independent Component Analysis

Independent component analysis seeks to determine how data is organized^{8,19,27}. This method assumes the measured signal X is a linear mixture of mutually independent source signals (S) and noise signals. One assumption to ICA is that the number of sources has to be known or estimated beforehand.

For the equation

$$X = AS \quad (I.1)$$

ICA aims to find an unmixing matrix (A^{-1}) which separates sources best. To solve this, W , the pseudoinverse of A , is calculated such that $Y = WX$, where $Y \approx S$. When mutual information between all sources is zero, ICA has reached a solution. Generally, fMRI analyses that incorporate ICA consider collected brain images as the mixture of spatially independent brain networks.

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