Chapter One
Introduction

1.1 Introduction

The effect of eye position on the three-dimensional (3-d) kinematics of human vestibular-evoked and saccadic eye movements is investigated in this thesis. In addition, possible mechanisms for producing eye position-dependent changes in the eye movement kinematics are discussed. A model-based approach is employed to determine the plausibility of the proposed physiological mechanisms.

The background to the experimental and modelling studies will be presented in this chapter, and the general aims of the project will be listed. The chapter ends with a section summarizing the organization of the thesis, and a list of publications and presentations relating to the project.

1.2 Background

The subdivision of the motor system responsible for moving the eyes, the ocular motor system, has two general functions: to keep the eyes fixed on targets of interest, and to move the eyes from one target to another. A number of classes of eye movement have evolved (see section 2.1), with each having differing properties and functions. The two classes of eye movement considered in detail in the current project are vestibular-evoked eye movements and saccadic eye movements.

Vestibular-evoked eye movements normally arise following stimulation of the vestibular apparatus in the inner ear. The vestibular system works in concert with the visual and proprioceptive systems to help maintain visual and postural balance when stationary and while moving. One of its specific functions is to produce eye movements that compensate for head movements, such as those that occur while walking or running,

thereby helping to stabilize images on the retina. If the head undergoes a sudden rotational movement to the left, for example, a compensatory eye rotation to the right is produced as a result of vestibular stimulation, thereby keeping the current image on the retina stable (see figure 1.1). The compensatory eye movement is reflexive and arises due to the action of the angular vestibulo-ocular reflex (aVOR).

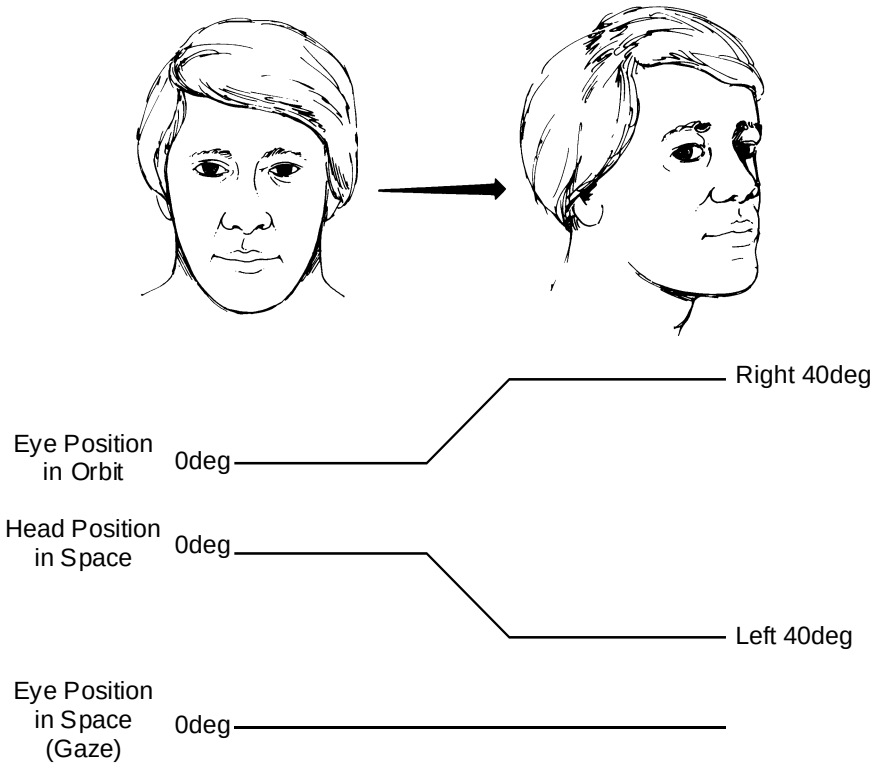

Figure 1.1 When the head is rotated 40° to the left, there is a rotation of the eye in the orbit of 40° to the right. Consequently, the direction of gaze remains constant, and the image on the retina remains stable. The eye movement is reflexive and arises due to the action of the aVOR (from Leigh and Zee 1999).

For the aVOR to bring about eye movements that stabilize the retinal image during angular head rotations, three criteria must be fulfilled: the eye and head velocities must be opposite in direction, the eye and head velocities must be equal in magnitude, and the eye and head rotation axes must be aligned in 3-d space. A number of investigators have shown that, during horizontal and vertical angular head rotations, these three criteria are approximately fulfilled when the eye is positioned near the centre of the ocular motor range at the start of the head rotation (see, for example, Aw et al. 1996a).

When the eye is not positioned near the centre of the ocular motor range at the start of the head rotation, these criteria are no longer fulfilled (Misslisch et al. 1994; Solomon et al. 1997; Thurtell et al. 1999; Misslisch and Hess 2000; Misslisch and Tweed 2001). Specifically, an increase in the eccentricity of eye position has been observed to result in increased misalignment between the eye and head rotation axes during angular head rotations.

Since the observed eye position-dependent changes in the aVOR were noted to be similar to eye position-dependent changes in the orientation of the eye rotation axis during saccadic eye movements, these phenomena are thought to arise by way of a common mechanism. Saccadic eye movements are rapid eye movements that function to quickly move the eyes from one target to another target of interest. The 3-d kinematic properties of saccadic eye movements have been extensively studied in the past (see, for example, Tweed and Vilis 1990). The contribution of various central structures, such as the caudal nucleus reticularis tegmenti pontis and the cerebellum, and peripheral structures, such as the so-called muscles pulleys (Demer et al. 1995), to producing eye position-dependent changes in saccadic (and, indeed, vestibular-evoked) eye movements is a subject of debate that will be addressed in detail in this thesis.

1.3 Aims

The main aim of the present series of studies was to demonstrate the presence of eye position-dependent changes in saccadic and vestibular-evoked eye movements, and to investigate the means by which these changes might come about. Both experimental and modelling approaches have been utilized to help achieve this aim.

The primary aim of the first study was to comprehensively describe the kinematic properties of saccadic eye movements in normal humans and humans with cerebellar atrophy. A second aim of the study was to elucidate the contribution made by the cerebellum in bringing about normal saccadic eye movements. The third aim of the first study was to determine how well the kinematic properties of normal saccadic eye movements were predicted by a 3-d model of the saccadic system that incorporates the

action of muscle pulleys (see section 2.3b). Data obtained in the study were directly compared with model predictions.

The aim of the second study was to determine how well the kinematic properties of vestibular-evoked eye movements were predicted by a 3-d model of the vestibular system that incorporates the action of muscle pulleys. To evaluate the accuracy of the model predictions, data obtained from a previous study (Thurtell et al. 1999) were compared directly with the model output.

1.4 Thesis Organization

The thesis is divided into three sections: literature review, methods, and findings. The literature review is presented in chapters 2-4. An introduction to the structure and function of the ocular motor system is given in chapter 2, with emphasis on saccadic eye movements. The structure and function of the vestibular system is reviewed in chapter 3, with emphasis on the aVOR, while chapter 4 contains a review of the experimental and theoretical literature on the 3-d kinematics of saccadic and vestibular-evoked eye movements.

Details of the study methods are presented in chapters 5-7. In chapter 5, the data acquisition system is described, while chapter 6 contains a description of the experimental protocols. In chapter 7, the data analysis and modelling procedures are discussed.

In chapters 8-10, the findings from the studies are presented and discussed. Since the findings from two separate studies are considered in this thesis, the results and discussion for each of these are presented in separate chapters (chapters 8 and 9), one per study. In chapter 10, conclusions from the studies are drawn and possible directions for future research are considered.

Finally, descriptions of important concepts and relevant laws governing rotations in 3-d space are not included in the text of the thesis. Rather, these are described and discussed in a self-contained body of text in the appendix.

1.5 Publications and Presentations

Some of the findings from the studies presented in this thesis were published in a refereed journal during the course of the project. All of the findings were presented at international and local conferences. A list of these publications and presentations is included below.

Refereed publication:

Thurtell MJ, Kunin M, Raphan T. Role of muscle pulleys in producing eye position-dependence in the angular vestibuloocular reflex: a model-based study. J Neurophysiol 84: 639-650, 2000.

Conference presentations:

Thurtell MJ, Black RA, Raphan T, Kunin M, Halmagyi GM. Role of muscle pulleys in producing eye position-dependence during high velocity head rotations. Soc Neurosci Abstr 25: 1649, 1999. (Poster; presented at the Society for Neuroscience Annual Meeting, Miami Beach, 23-28 October 1999.)

Thurtell MJ, Raphan T, Black RA. Rectus muscle pulleys and their role in producing eye position-dependence in the vestibulo-ocular reflex. (Slides; presented at the Neuro-Otology Society of Australia 9th Annual Meeting, Sydney, 13-14 November 1999.)

Thurtell MJ, Raphan T, Kunin M, Black RA, Halmagyi GM. How mathematical models can predict anatomy and physiology: rectus muscle pulleys and vestibular mechanisms. (Poster; presented at the Australian Association of Neurologists Golden Jubilee Scientific Meeting, Melbourne, 15-19 May 2000.)

Thurtell MJ, Black RA, Raphan T, Todd MJ, Halmagyi GM. Three-dimensional kinematics of saccadic eye movements in humans with cerebellar atrophy. (Slides; presented at the Neuro-Otology Society of Australia 11th Annual Meeting, Sydney, 20-21 October 2001.)