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Minireview

The coordination of binocular eye movements: Vertical and torsional alignment

James S. Maxwell *, Clifton M. Schor

University of California, 360 Minor Hall, Berkeley, CA 94720-2020, USA

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Abstract

Precise binocular alignment of the visual axes is of utmost importance for good vision. The fact that so few of us ever experience diplopia is evidence of how well the oculomotor system performs this function in the face of changes due to development, disease and injury. The capacity of the oculomotor system to adapt to visual stimuli that mimic alignment deficits has been extensively explored in laboratory experiments. While the present paper reviews many of those studies, the primary focus is on issues involved in maintaining good vertical and torsional alignment in everyday viewing situations where the parsing of muscle forces may vary for the same horizontal and vertical eye positions due to changes in horizontal vergence and head posture.

Keywords: Phoria; Adaptation; Binocular; Skew; Ocular counterroll; Torsion; Cyclovergence; Hering; Listing; Eye alignment; Phoria adaptation; Otolith-ocular reflex; Vergence

1. Introduction

This review concerns the seemingly simple yet complex task of keeping the two eyes in good alignment. This is an important function of the oculomotor system since poor alignment produces retinal disparities and disparities of more than 0.25° can result in double vision and a degradation of stereopsis (Schor & Tyler, 1981). It is also desirable to keep the lines of sight of the two eyes converged on an object of interest even if the view of one eye is temporarily occluded as often occurs. Torsional alignment of the eyes is important for achieving optimal stereo-depth perception (Schreiber, Crawford, Fetter, & Tweed, 2001). The present review will be limited to a discussion of the adaptation and coordination of vertical and torsional eye movements since the literature concerning horizontal coordination is far too extensive to cover in a relatively short review. In addition, we have focused most of our own adaptation experiments on vertical and torsional eye movements because they are free from the confounding issue of voluntary vergence as is the case with horizontal vergence.

The terms *vergence* and *skew* will be used to signify the difference in position between the two eyes regardless of viewing condition whereas *fusion* indicates that viewing is binocular and *phoria* indicates that binocular alignment is tested in the absence of a fusible stimulus for the dimension being measured. For example, a bulls-eye pattern viewed binocularly has fusible stimuli for horizontal and vertical eye alignment but not for torsion and could be used to measure cyclophoria.

1.1. Vertical vergence and coordinate systems

Until fairly recently, slight regard has been paid to specifying coordinate systems when reporting oculomotor measurements. Of late, however, the desire to record three-dimensional eye movements has resulted in greater attention to coordinate systems since torsional measurements are inherently coordinate-system dependent. Specifying a coordinate system for horizontal and vertical eye movements is also important, however, especially when presenting visual targets that require convergence, since tertiary

* Corresponding author. Fax: +1 510 643 5109.
E-mail address: jsm@socrates.berkeley.edu (J.S. Maxwell).

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eye position measurements will have different horizontal and vertical values depending on the coordinate system used. The three most widely used coordinate systems for measuring eye movements are those named for Fick, Helmholtz and Listing. These coordinate systems are often illustrated as a series of rotations in which the rotational axes are gimbaled so that they either move with the eye (eye-fixed) or are stationary with respect to the orbit (head-fixed). Fig. 1A shows that if the eye were to rotate about a head-fixed vertical axis, the line of sight projected onto a tangent screen describes a curved line. From the opposite point of view, a point projected from the screen to the back of the globe would inscribe a minor circle (like the lines of latitude on a globe). If the eye were to rotate about an eye-fixed axis, on the other hand (Fig. 1B), then the line of sight describes a straight line when projected onto a flat screen, or again, from the opposite point of view, a point projected onto the back of the eye describes a great circle (like the lines of longitude) when the globe rotates. Measured in Fick coordinates, the eye appears to move as though it were gimbaled so that horizontal rotations were about a head-fixed axis and vertical rotations were about an eye-fixed axis. Measured in Helmholtz coordinates, the eye appears

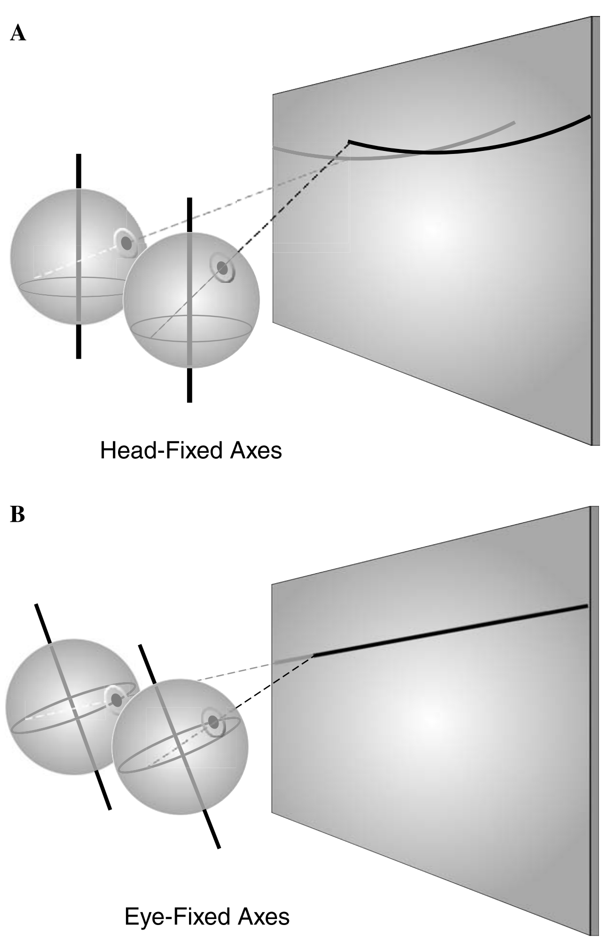

Fig. 1. (A and B) Illustrate the effect of horizontal globe rotations about vertical axes for near targets on a tangent screen. Different reference systems produce different measurements when the eyes are converged and in tertiary positions.

to move as though horizontal rotations were about an eye-fixed axis and vertical rotations were about a head-fixed axis. It is clear from the illustration why some authors advocate the use of Helmholtz coordinates for describing vertical eye movements because horizontal eye movements do not change the elevation of the eyes relative to each other. If the eyes were actually gimbaled this way, therefore, no vertical vergence would be required to track near targets in tertiary eye positions, that is, they would automatically be aligned. If, on the other hand, the eyes were gimbaled in a Fick-like fashion, then vertical vergence would be required in order to binocularly foveate near, tertiary targets.

Just how well aligned vertically are the two eyes? For targets placed directly in front of normal subjects, vertical alignment with one eye covered is quite good: on the order of 0.10–0.16° of vertical phoria (Kapoula, Eggert, & Bucci, 1996; van Rijn, ten Tusscher, de Jong, & Hendrikse, 1998). Vertical alignment is a more difficult problem for near targets in tertiary positions, where the target is closer to one eye than the other thereby creating vertical disparities and one might expect that good alignment would suffer. In an extraordinary coincidence, three papers concerning the binocular coordination of vertical eye movements during horizontal vergence were presented at a single meeting (Collewijn, 1994; Schor, Maxwell, & Stevenson, 1994; Ygge & Zee, 1995). The essence of each of these experiments was to have subjects fixate targets at near, tertiary eye positions and measure vertical eye alignment open loop, i.e., without binocular feedback for vertical vergence, to see whether or not the lines of sight of the two eyes still intersected. All three groups found that the vertical axes did intersect meaning that there was no vertical vergence error. Interestingly, the three groups of researchers interpreted essentially same data in three different ways: Collewijn et al., noted that vertical eye position is expressed best using Helmholtz coordinates and in Helmholtz coordinates the eyes were well aligned vertically during horizontal vergence. Ygge and Zee presented their results in Fick coordinates, and in Fick coordinates, a horizontal rotation about the vertical axis into a tertiary eye position results in a vertical misalignment of the two lines of sight if left uncompensated. The fact that the lines of sight intersected at tertiary targets indicated to these authors that the oculomotor system automatically corrects for such potential misalignments. Schor, Maxwell & Stevenson essentially avoided dealing with coordinate system issues by simply comparing the vertical alignment of the eyes with and without feedback for vertical vergence (horizontal vergence was always closed-loop) for both near and far tertiary targets. They found that vertical eye alignment was nearly identical (within 0.25°) whether eye movements were between far, tertiary targets or between near, tertiary targets and whether the targets were open-loop (only one eye could see the vertical targets) or closed-loop for vertical vergence. Whether the accurate alignment of the eyes was the result of mechanical gimbaling or the result of adaptive mechanisms could not be