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Dynamic aspects of trochlear nerve palsy*

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No color figures

ABSTRACT

Trochlear nerve palsy leads to kinematic aberrations of both the paretic and the unaffected eye. During dynamic head roll, the rotation axis of the covered - paretic or unaffected - eye deviates inward, while the rotation axis of the viewing - paretic or unaffected - eye aligns with the line of sight; this convergence of rotation axes increases with gaze moving in the direction of the unaffected eye. During downward saccades, the trajectories of both eyes curve towards the unaffected side; these curvatures increase when the head is rolled to the affected side and gaze directed to the unaffected side. Hence, during both vestibular evoked and saccadic ocular movements, the unaffected eye shows similar kinematic aberrations as the paretic eye. While aberrations of the paretic eye can be explained by decreased force of the superior oblique muscle (SO), aberrations of the unaffected eye may be due to increased force parallel to the paretic SO in the unaffected eye in accordance with Hering's law. This law, which forms the basis of conjugate eye movements, also seems to govern eye displacements in unilateral eye muscle palsy.

INTRODUCTION

For monocular viewing, Hering's law of equal innervation implies that for each position of one eye there is only one corresponding position of the fellow eye, independent of which eye is covered (Hering, 1868). This law is also valid in the presence of extra-ocular muscle palsy, but here the deviation between the three-dimensional positions of the two eyes increases as gaze is shifted toward the pulling direction of the paretic muscle (Straumann *et al.*, 2003; Zee *et al.*, 1984). Thus, in the static condition with one eye fixing upon a visual target and the other eye covered, the position of the covered eye is always unique relative to the viewing eye, no matter whether the paretic or the non-paretic eye is covered.

While the validity of Hering's law in eye muscle palsy is generally accepted for static eye positions, the law could be violated during eye displacements. For instance, in abducens nerve palsy, clinicians frequently observe an apparent overshooting of the unaffected adducting eye during saccades in the direction of the lateral rectus muscle of the other eye. This clinical sign, however, is assessed during binocular viewing, which may lead to an activation of the vergence system and, in turn, to a decrease of the squint angle after the saccade. In other words, clinical observation or measurement of ocular movements with both eyes viewing is not sufficient to dismiss the possibility that Hering's law can be extended to binocular positions during gaze displacements in the absence of vergence movements.

In this paper, we ask whether Hering's law is valid during the vestibulo-ocular reflex and during saccades in patients with eye muscle palsy. We chose to study this question in trochlear nerve palsy, because a weakness of the superior oblique muscle

barely restricts the ocular motor range of the affected eye, which facilitates the kinematic analysis of binocular movements. Here we report on the data from two different paradigms, in which we controlled the movement of the viewing eye, while the fellow covered eye was free to move. First, we rotated patients about their naso-occipital axis during monocular fixations along the horizontal meridian and determined the rotations axes of both eyes. Second, we elicited downward saccades in different static whole-body roll positions and compared the saccadic deviations of the two eyes from a straight trajectory between saccadic onset and offset. Our hypothesis was that the relation between the rotation axes (VOR paradigm) or positional vectors (saccade paradigm) of the two eyes is always in accordance with Hering's law.

Since the pulling direction of the superior oblique muscle includes, besides a vertical component, a considerable torsional component, it is indispensable to record eye movements of patients with trochlear nerve palsy about all principle axes of rotation (horizontal, vertical, torsional). Here we applied two different technologies. For the VOR paradigm, we used the dual search-coil technique, while for the saccade paradigm we chose 3D video-oculography to bypass the problem of saccadic torsional coil artifacts (Bergamin et al., 2004). - Part of the data presented in this paper originates from experiments that were published elsewhere (Weber *et al.*, 2004)

METHODS

Subjects

We tested patients with untreated congenital or acquired unilateral trochlear nerve palsy. Informed consent was obtained from the subjects after the experimental procedure was explained. The protocol was approved by a local ethics committee and was in accordance with the ethical standards laid down in the Declaration of Helsinki for research involving human subjects.

Vestibular paradigm

Subjects were seated upright on a turntable with three servo-controlled motor driven axes (prototype built by Acutronic, Jona, Switzerland). The head was restrained with an individually molded thermoplastic mask (Sinmed BV, Reeuwijk, The Netherlands) and was positioned such that the center of the interaural line was at the intersection of the three axes of the turntable. Pillows and safety belts minimized movements of the body. Movements of both eyes were recorded in three dimensions with dual search coils manufactured by Skalar (Delft, The Netherlands). A chair-fixed coil frame (side length, 0.5 m) that produced three orthogonal magnetic fields with frequencies of 80, 96, and 120 kHz surrounded the subject's head. The signals were amplified and multiplexed before passing through the turntable slip rings. A high performance 12-bit digital signal processor computed a Fast Fourier transform in real time on the digitized search coil signal to determine the voltage induced in the coil by each magnetic field (system manufactured by Primelec, Regensdorf, Switzerland). Rotation vectors (for positions) and angular velocity vectors (for rotation axes) of both eyes were computed off-line from the coil signals. In patients with left-sided trochlear nerve palsy, the directions of three-dimensional eye position

were horizontally mirrored, as if the right eye had been affected by the palsy. Subjects monocularly fixed laser dots projected on a spherical screen at a distance of 1.4 m, whereas the other eye was covered. The dots were located straight ahead and at $\pm 20^\circ$ eccentric head-fixed positions. During visual fixation, subjects were oscillated about the naso-occipital (roll) axis with a frequency of 0.3 Hz and an amplitude of $\pm 35^\circ$.

Saccade paradigm

In upright, 45° left ear down, and 45° right ear down whole-body roll positions, subjects monocularly tracked a jumping laser target projected on the spherical screen, while the fellow eye was covered. Three-dimensional eye movements were binocularly recorded at 200 Hz with a 3D videooculography system (Chronos Eye Tracker Version 1C/2003, Chronos Vision GmbH, Berlin, Germany) mounted on the thermoplastic mask. To optimize pupil tracking, pupils were constricted with pilocarpine 0.5% eye drops 30 minutes before recording. Vertical saccades with amplitudes of 10° were recorded at -10° , 0° and 10° horizontal eccentricity. The laser dot jumped to and fro every 3 seconds without randomization. Raw video data were processed with the iris tracker software (Version 2.1.6.1., Chronos Vision GmbH).

RESULTS

Fig. 1 depicts average horizontal angles of ocular rotation axes relative to straight ahead, while subjects were oscillated about the naso-occipital axis and fixed upon horizontal visual targets (circles: straight head; down triangles: 20° right; up triangles: 20° left). The horizontal angles of ocular rotation axes (x-axis: paretic right eye, y-axis: unaffected left eye) are plotted against each other, while either eye is viewing (filled symbols: right eye covered, left eye viewing; empty symbols: right eye viewing, left eye covered). The example (data from a patient with congenital trochlear nerve palsy) on the left panel of Fig. 1 demonstrates that the correlated horizontal angles between the rotation axes of the two eyes fall almost on a single line which is shifted relative to the line computed from healthy subjects (solid line). Average values (± 1 SD) of all 12 patients with trochlear nerve palsy (paretic eye always on the right side; see Methods) are shown on the right panel. Again, independent of whether the right paretic eyes or the left unaffected eyes were viewing, there was an almost identical linear relationship between the horizontal angles of binocular rotation axes.

/ Figure 1 about here */*

Fig. 2 shows visually elicited downward saccades in a typical patient with right-sided acquired trochlear nerve palsy. Visual stimuli were given at different horizontal eccentricities (straight ahead, 10° right, 10° left). The amplitude between stimulus onset and offset was always 10°. Already in the upright position (Fig. 2A, middle panel), the saccades of both the covered paretic right eye and the viewing unaffected left eye curve away from the paretic eye. Curvatures increase in the 45°

Bielschowsky whole-body roll position (Fig. 2A, right panel; tilt towards the side of the paretic eye) and decrease in the opposite whole-body roll position (Fig. 2A, left panel). When the maximal saccadic horizontal deviations of the two eyes are plotted against each other (Fig. 2B), data points scatter along the same line for saccades in all three whole-body roll positions (circles: horizontal deviations during vertical saccades at different horizontal eccentricities in upright position; up triangles: in 45° left ear down position; down triangles: in 45° right ear down position). The same pattern, but with individual magnitudes of horizontal saccadic curvatures, was found in the majority of patients with acquired or congenital trochlear nerve palsy (data not shown).

/* Figure 2 about here */

DISCUSSION

In the absence of vergence, the neural signals that drive the extra-ocular muscles of one eye also drive the yoked muscles of the fellow eye to maintain conjugate binocular positions. This “equal innervation” of the two eyes, known as Hering’s law (Hering, 1868), is still preserved in the case of monocular eye muscle palsy, although binocular positions become disconjugate. The preservation of Hering’s law in one-sided eye muscle palsy can be verified by plotting the positions of the two eyes against each other, while one eye is covered and the other eye is fixing upon visual targets at various eccentricities (Zee *et al.*, 1984). Independent of whether the paretic or unaffected eye is covered, the data points fall on the same curve, which is exactly what one expects if the innervation is strictly binocular. In this paper we demonstrated that Hering’s law can be extended to binocular movement trajectories.

During the torsional vestibulo-ocular reflex, the rotation axes of the two eyes are relatively fixed and parallel, when the viewing eye is fixing a target at infinity (Bergamin and Straumann, 2001). While the stability of rotation axes is also preserved in patients with a one-sided trochlear nerve palsy, the rotation axis of the covered eye is rotated inward (Weber *et al.*, 2004). As shown in Fig. 1, the correlated horizontal angles of ocular rotation axes that were determined during monocular fixations of horizontally displaced visual targets scattered close around the same line, independent on whether the paretic or unaffected eye was viewing. This finding, in turn, is compatible with the view that Hering’s law also applies to eye movements during the vestibulo-ocular reflex (VOR). We anticipate that similar results can be found in other extra-ocular muscle palsies and for different VOR directions.

For downward saccades, both the inferior rectus and the superior oblique muscles contract. If the superior oblique muscle is paretic, we expect that, during the saccade, the affected eye deviates in the pulling direction of the inferior rectus muscle. Indeed, there is dynamic extorsion of the paretic eye during downward saccades as described by Steffen et al. (Steffen *et al.*, 2007). These authors already noted that the unaffected eyes showed similar torsion in the conjugate direction (intorsion), which casts doubts on whether the saccadic transient deviation of the affected eye is really a direct mechanical consequence of the muscle paresis. In this paper, we concentrated on the saccadic horizontal transients, i.e. curvatures of trajectories during downward saccades in patients with trochlear nerve palsy. These curvatures generally increase with subjects rolling their head toward the side of the affected eye. We found that the magnitude of curvatures was almost the same in the paretic and the unaffected eyes. This finding suggests that aberrant saccadic trajectories cannot be explained by the geometry of a paretic eye muscle alone, but is the consequence of neural adaptation to the paresis and, as a result, is visible on both eyes in accordance with Hering's law.

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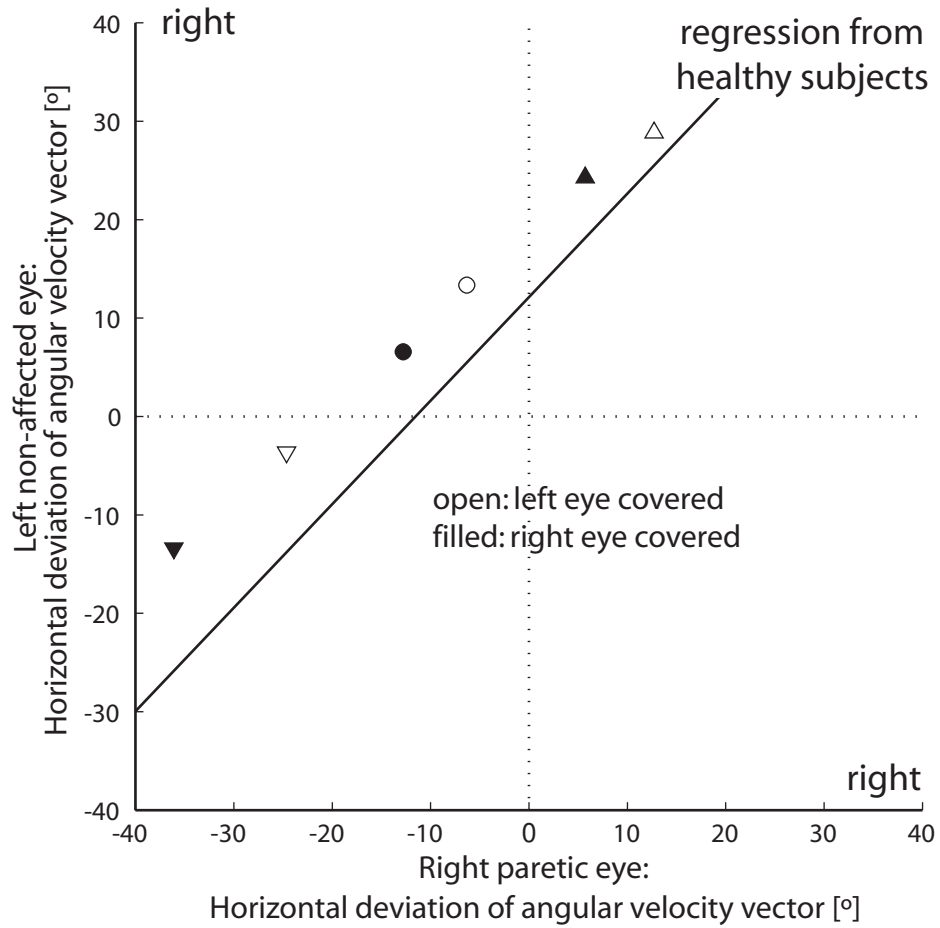
LEGENDS

Figure 1: Average orientation (angle in degrees) of ocular rotation axes in the horizontal plane relative to straight ahead during oscillations about the naso-occipital axis (amplitude: $\pm 35^\circ$; frequency: 0.3 Hz). One eye was always viewing, while the other eye was covered. Abscissa: right paretic eye(s). Ordinate: left unaffected eye(s). Empty symbols: right paretic eye(s) viewing. Filled symbols: right paretic eye(s) covered. Circles: viewing of straight ahead target. Down triangles: viewing of 20° right target. Up triangles: viewing of 20° left target. Dotted lines: zero angles for right (vertical line) or left (horizontal line) eye. Solid lines: regression from a population of healthy subjects. Note that data points scatter linearly independent of whether the paretic eye is viewing or covered, but they are shifted to the left relative to the normal regression line. **(A)** Typical patient with congenital trochlear nerve palsy on the right side. **(B)** Averages ± 1 SD of all 12 patients with trochlear nerve palsy. In patients with left-sided trochlear nerve palsy, the directions of three-dimensional eye position were horizontally mirrored.

Figure 2: Mean traces of downward saccades in a patient with acquired right-sided trochlear nerve palsy. Visual targets were presented at -10° , 0° , and 10° horizontal eccentricities. Onset targets were 5° above and offset targets 5° below the horizontal meridian. **(A)** Horizontal (abscissa; right is positive) and vertical (ordinate; up is positive) eye positions during saccades. Gray traces: right eye. Black traces: left eye. Note that trajectories of both eyes deviate to the left before curving back. Curvatures increase in the 45° right ear down whole-body position (right panel; Bielschowsky

position) and decrease in the 45° left ear down whole-body position (left panel; anti-Bielschowsky position). **(B)** Maximal horizontal deviations from straight lines connecting saccadic onsets and offsets. Abscissa: covered right paretic eye. Ordinate: viewing left eye. Circles: data in upright position. Up triangles: data in 45° left ear down position. Down triangles: data in 45° right ear down position. Note that data points scatter close to a 45° line through zero, which indicates perfect conjugacy of maximal saccadic horizontal deviations.

Example



12 patients

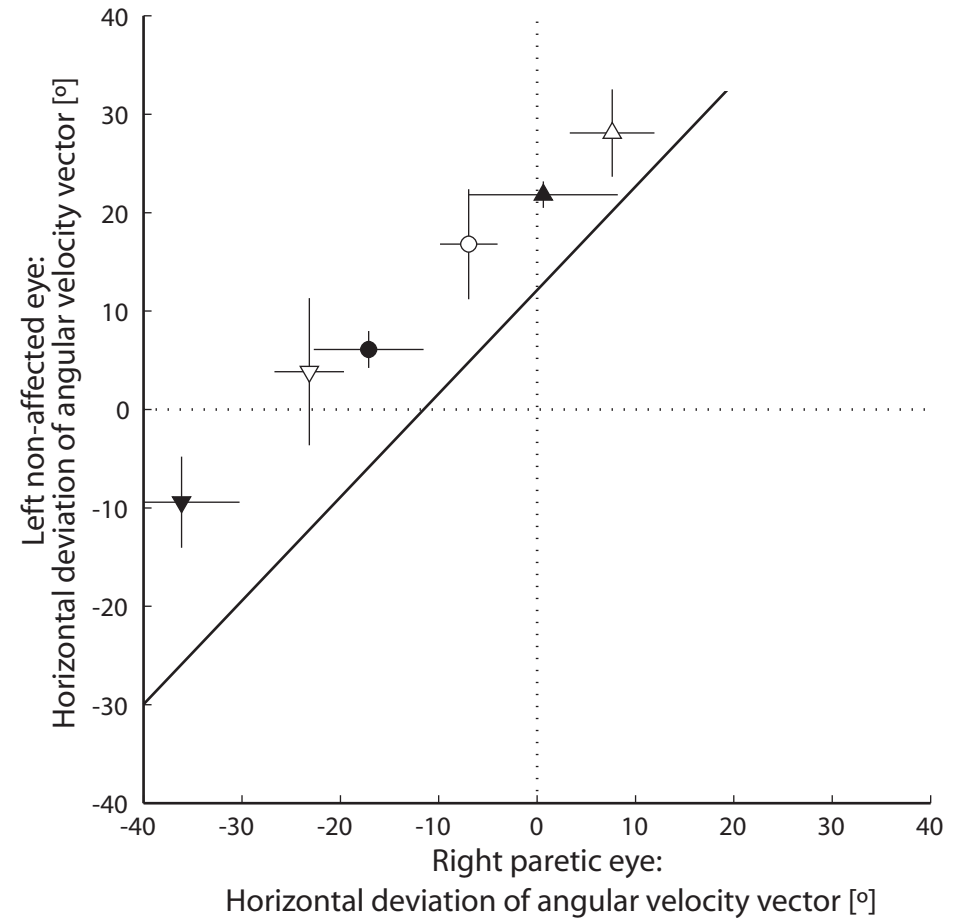


Fig. 1

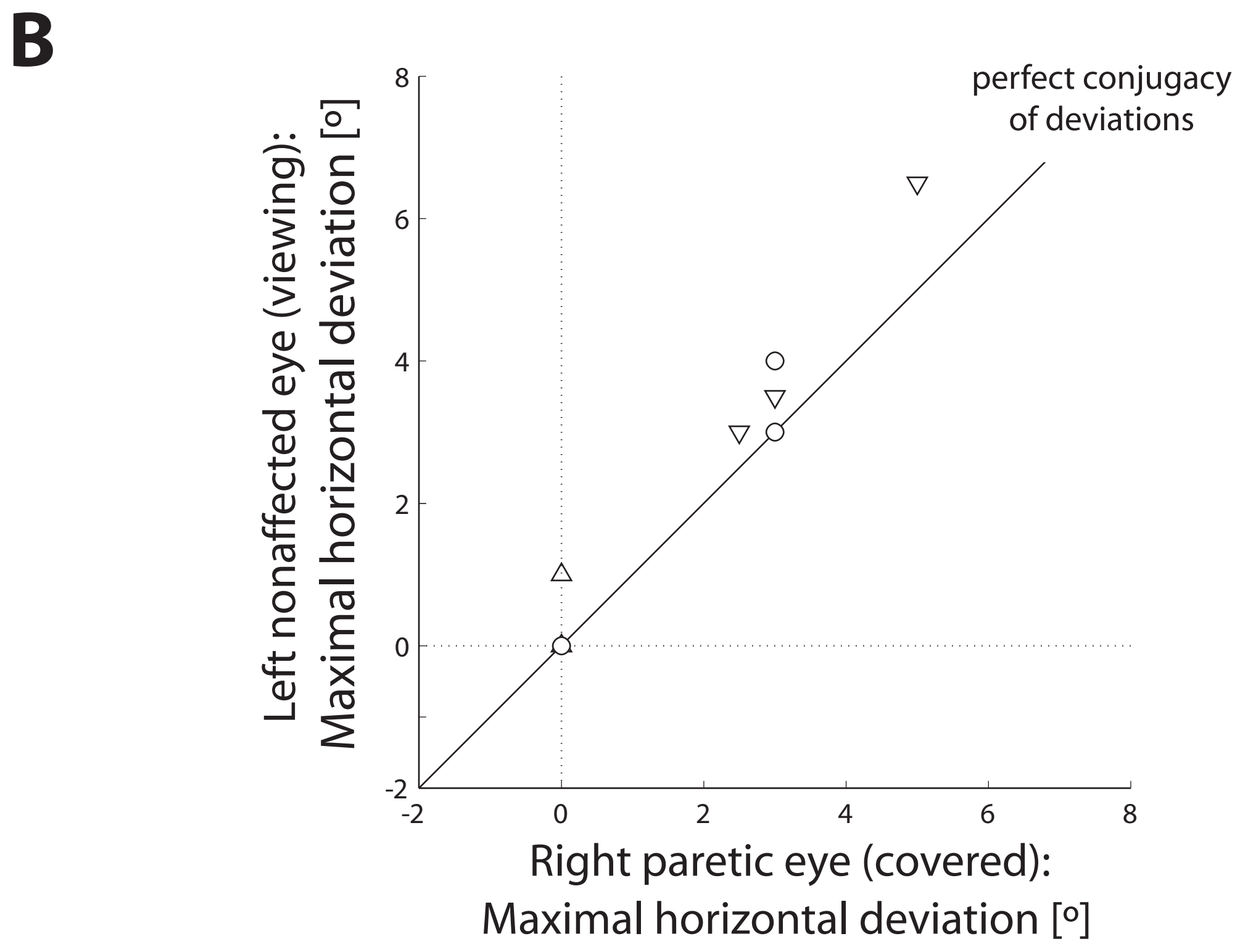
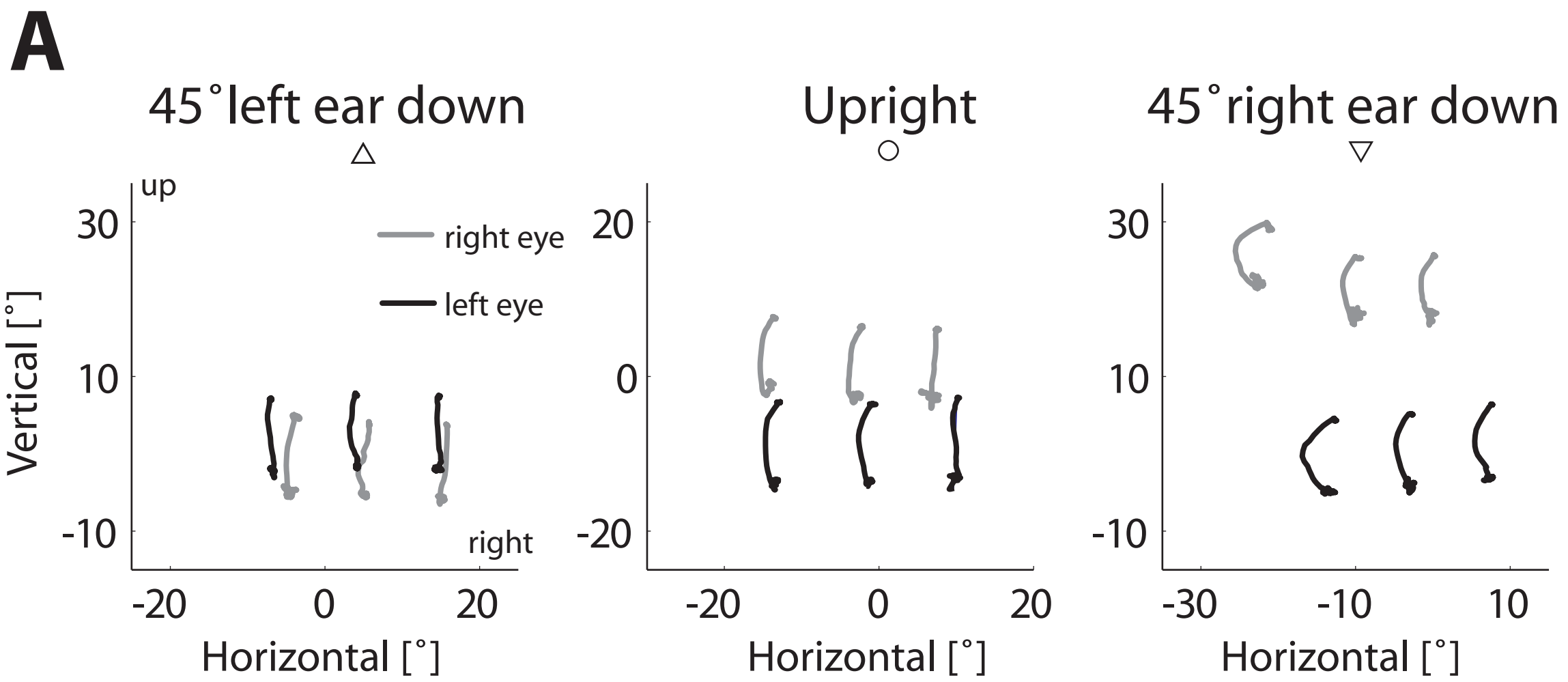


Fig. 2