

Optimizing Gaze Control in Three Dimensions

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Horizontal and vertical movements of the human eye bring new objects to the center of the visual field, but torsional movements rotate the visual world about its center. Ocular torsion stays near zero during head-fixed gaze shifts, and eye movements to visual targets are thought to be driven by purely horizontal and vertical commands. Here, analysis of eye-head gaze shifts revealed that gaze commands were three-dimensional, with a separate neural control system for torsion. Active torsion optimized gaze control as no two-dimensional system could have, stabilizing the retinal image as quickly as possible when it would otherwise have spun around the fixation point.

The human eye rotates with three degrees of freedom: horizontally, vertically, and torsionally (1, 2). With few exceptions, theories of

vision and eye movement have ignored rotations about the line of sight. One reason is Listing's law (1, 3, 4), which states that ocular torsion stays near zero during head-fixed gaze shifts. This has been taken as confirmation that gaze is driven by purely horizontal and vertical commands. Here we show that Listing's law is just one mode of gaze control, valid only when the head is stationary.

When eye and head join forces to transport the gaze line, the logistics are complex. For one thing, the eye is quicker than the head—it reorients more swiftly when an interesting object

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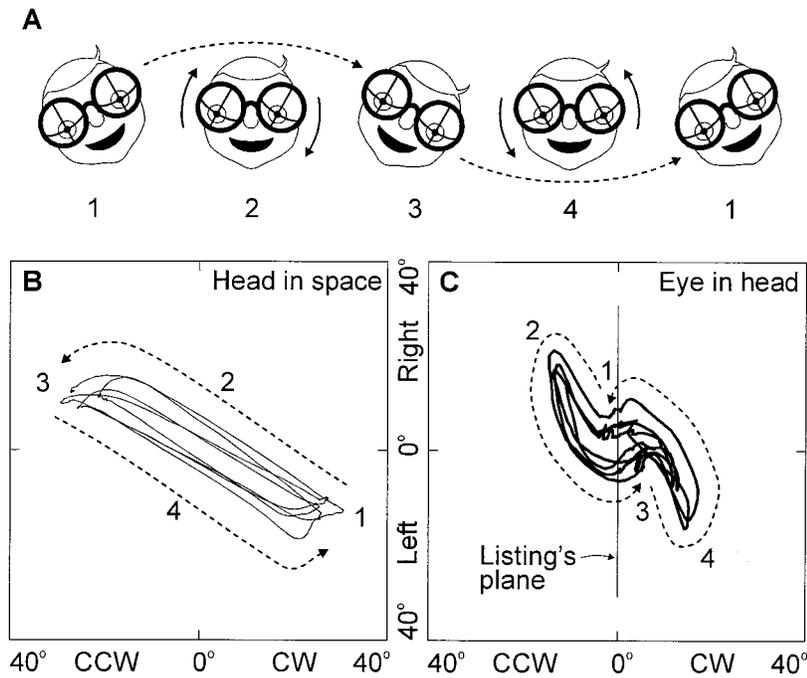


Fig. 1. (A) Gaze task. The person started in position 1, with the head turned $\sim 30^\circ$ CW and the eyes directed $\sim 20^\circ$ down in the head, looking at a laser spot projected on a spherical screen 1 m away. Then the spot jumped 20° to the right, and the person made an eye-head movement to refixate it. The head's contribution to this gaze shift, in keeping with instructions given beforehand (7), was a rolling movement ending up in position 3. After a brief pause, the laser spot jumped back to the person's left, evoking a movement back to position 1. Positions 2 and 4 show eye and head positions in mid-movement. (B) Angular head position in space during several repetitions of this task (8). Torsional head rotation (CW/CCW) is indicated on the abscissa; horizontal head rotation (right/left) is indicated on the ordinate. (C) The same components of eye position in the head. Vertical components are not shown in (B) and (C) because the motions were uneventful in that dimension.

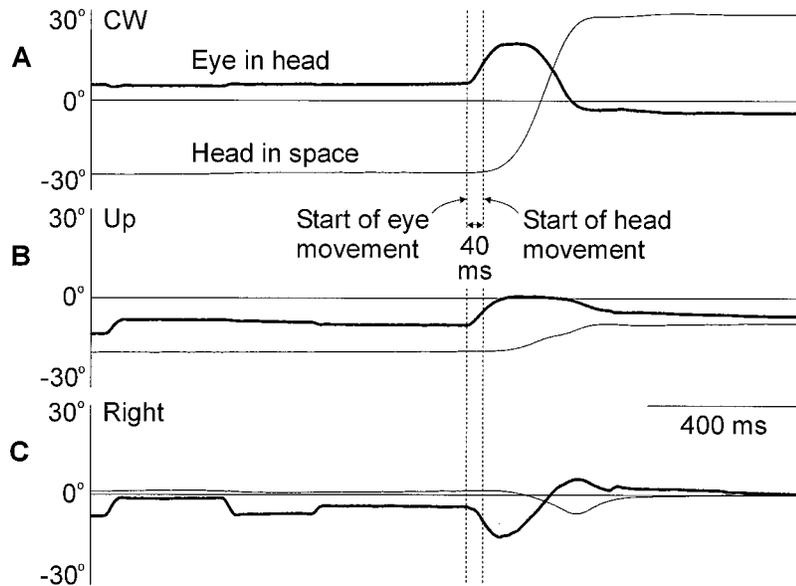


Fig. 2. Position versus time for the eye in the head (thick lines) and the head in space (thin lines). (A) Torsional eye and head motion. (B) Vertical motion. (C) Horizontal motion. The task is as in Fig. 1. For the first 1 s of the traces, the head is stationary and the eye makes small gaze shifts. Ocular torsion stays virtually constant at about 4° CW. Then the eye-head gaze shift begins: The head rolls almost 60° CW; the eye rapidly twists 15° CW and then reverses and rolls 20° CCW. This eye motion starts 40 ms before the head moves, which shows that it is not triggered by head-motion sensors in the inner ear.

appears in the visual periphery. The eye swivels rapidly to the visual target and locks on, whereas the head reorients itself more slowly (5, 6). Computer simulations suggested that we could test for active control of ocular torsion by examining gaze shifts involving large torsional head rotations.

We chose a gaze task that was like watching a mouse darting back and forth along a floorboard (7) (Fig. 1A). In all study participants, the eye moved to its final position in space faster than the head, turning not just horizontally and vertically but also torsionally, so that midway through the movement, the eye was twisted far clockwise or counterclockwise (CW or CCW) relative to the head, as shown in panels 2 and 4 of Fig. 1A. It then held still in space as the head completed its motion. Panels B and C in Fig. 1 show a typical participant's head and eye rotations in this task (8). Each eye movement began and ended near the plane of zero torsion, called Listing's plane (4). It is known that static eye positions are slightly counterrolled when the head tilts (2), which is why the person's eye was twisted about 3° CCW in position 1 and about the same distance CW in position 3.

What was interesting was the eye's path. It did not simply jump between positions 1 and 3 but instead took exceptionally wide horizontal and torsional detours (9). For this person, the range of torsion amounted to 32° , from 17° CW to 15° CCW. Across all four participants, the torsional range varied between 22° and 34° , with an average of 29° . These ranges were enormous compared to the values of 2° to 4° that were seen during head-fixed gaze shifts (4).

Were these huge torsional excursions truly visually evoked gaze shifts, or were they driven by head-motion sensors in the vestibulum? They were not vestibular, because they were usually under way 20 to 60 ms before the head began moving (Fig. 2). Thus, the movements were not triggered by head motion but were voluntary gaze shifts (10).

The gaze task (Figs. 1 and 2) was chosen for its large torsional component, but everyday "looking around" also involves substantial head torsion, ranging over $\pm 12^\circ$ (11, 12). When we tested one of our participants on natural eye-head gaze shifts to visual targets at 90° eccentricity (7), we found the same pattern: transient ocular torsion over $\pm 6^\circ$, a range that was only 40% as large as that above, but still substantial. Thus the same motor strategy was used in both tasks, but the one in Figs. 1 and 2 better revealed the torsional potential of the system.

What was the purpose of the eye's transient torsion? As Fig. 1A suggests, the eye twisted to anticipate the coming torsional motion of the head. By so doing, it reached its final position in space long before the head motion was finished. From then on, the eye was stable in space, and so the visual world

remained stationary on the retina. Image blur was reduced (13), and visual analysis was simplified in other ways as well. For example, a stationary retinal image could be analyzed by a single set of orientation columns in the visual cortex, whereas a spinning image would excite a continuously changing array of columns (14).

So active torsion allowed the eye to stabilize its target image at the earliest possible moment. But this speed came at a price: As shown in Figs. 1C and 2, the eye took an indirect path relative to the head, spinning about the line of sight at up to 200° per second for 80 ms and then unwinding back to near-zero torsion over 200 ms. That the brain tolerated this detour showed that it put more weight on getting the eye on target quickly than on saving the eye muscles work.

To protect the orbital tissues, eye rotation is kept within certain boundaries (6)—about 40° horizontally and vertically and 15° torsionally. When these boundaries were taken into account, the eye trajectories in Fig. 1C could be explained quantitatively. Figure 3 shows a computer simulation of a model (12) that drove the eye as quickly as possible to its final position in space, given the above limits on its motion in the head. The resulting eye trajectories matched the data very well. The same model also mimics head-fixed gaze shifts and eye-head movements with more moderate head torsion (12), which suggests that all these movements are generated by a single gaze-control system.

The present data show that at least two aspects of this model are almost certainly correct. First, ocular torsion was under active neural control. The eye muscles were capable of rolling the eye over a torsional range of more

than 30° (Fig. 1C), so the fact that torsion usually stays near zero (1, 3, 4) must reflect the careful tuning of the neural commands that activate the muscles. And this torsion-control system does not simply clamp ocular torsion, relative to the head, near zero. In our gaze task, it twisted the eye 15° CW or CCW, seeking a position in space that had been chosen so that, when the upcoming head motion was finished, the eye was back near Listing's plane.

Second, eye motion to a visual target was not determined by the retinal location of the target. We asked our participants to make the same gaze shifts as those shown in Fig. 1A, but with the head stationary. They held their heads still, 30° CW or CCW, as shown in panels 1 and 3, and they made head-fixed gaze shifts in response to the same visual input as before. Unsurprisingly, their eyes performed roughly fixed-axis rotations, staying within 2° of Listing's plane, as is usual in head-fixed gaze shifts (4). Gone were the wide loops with 15° of torsion. Thus the same sensory signals generated entirely different eye motions depending on whether a head movement was planned.

Our findings support the view that gaze is a three-dimensional control system, optimized to serve vision. When it wants to redirect the gaze line, the brain chooses desired orientations for the head and the eye, both defined in a space-fixed frame. Feedback loops drive head and eye toward their goals, though the eye's path may be deflected by its motion boundaries (6). The eye arrives at its target first and locks on, hanging suspended in space as the head rotates around it. When the head comes to a halt, ocular torsion relative to the head has returned to near zero, and the eye is poised for the swiftest possible response to the next visual target (15).

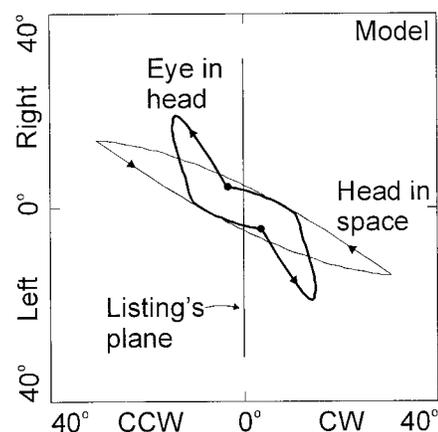


Fig. 3. A computer simulation of an optimized model of gaze control (12) matches the observed trajectories, including the eye's extreme deviations from Listing's plane. The eye stays near zero torsion between movements. During gaze shifts it takes the fastest possible path to its final position in space, with no constraint on torsion except that it stays less than 15° relative to the head.

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7. Our four participants were healthy, aged 30 to 38, and gave informed consent. They were instructed to look to the target spot using a fast combined motion of eyes and head, with the head ending up 30° CW or 30° CCW. Similar results were obtained for torsional gaze shifts while looking up and for "natural" gaze shifts, in which the person was given no instructions about final head position but simply looked between four targets—up-right, down-right, down-left, and up-left—at 90° eccentricity. These latter gaze shifts

were made in pseudorandom order and followed spoken commands.

8. The position of the left eye was recorded at 375 samples per second with the scleral-search-coil technique devised by D. A. Robinson [*IEEE Trans. Biomed. Electron.* **BME-10**, 137 (1963)]. Head position was recorded at the same rate with the use of search coils fastened to a lightweight bar molded to fit the person's teeth. Electrical signals from the eye and head search coils were converted to quaternions with the use of algorithms from D. Tweed, W. Cadera, and T. Vilis [*Vision Res.* **30**, 97 (1990)]. For an oculomotor introduction to quaternions, see G. Westheimer, *J. Opt. Soc. Am.* **47**, 967(1957); D. Tweed and T. Vilis, *J. Neurophysiol.* **58**, 832 (1987); or T. Haslwanter, *Vision Res.* **35**, 1727 (1995).
9. Our best performing participant showed a range of 16° CCW to 18° CW, tying the world record for human ocular torsion. A. P. Petrov and G. M. Zenkin [*Vision Res.* **13**, 2465 (1973)] also had a study participant who reached 18°, but by a different mechanism: Their participant was rotated torsionally in the dark; the eye movements were not gaze shifts to visual targets but vestibular responses to the head rotation, and they opposed the head's motion; whereas in our study the eye rolled the same way as the head and before it. R. Balliet and K. Nakayama [*Invest. Ophthalmol.* **17**, 303 (1978)] trained people to rotate their eyes torsionally while keeping their heads still. The training, which involved torsional visual feedback, allowed them to increase their torsional range by about 0.8°/hour, so that after 35 hours of training, the best performing person could move over a range of 26.5°. That result showed that the oculomotor system has torsional plasticity, whereas the present findings show that circuits for torsional gaze control are active in normal untrained humans. Our participants practiced the gaze task in Fig. 1 at most five times (that is, for only a few seconds) before recording began, and they showed the full torsional range of eye motion, or very close to it, on the first recorded trial.
10. The eye's return motion, when it came back toward Listing's plane while staying locked on the visual target, likely was vestibularly driven; but the initial outbound torsion, which anticipated the upcoming head turn, was not. In the outbound stage, the three-dimensional gaze system rotated the eye to its desired position in space and then locked on by activating the vestibuloocular reflex. This reflex uses vestibular information to monitor head velocity and counterrotates the eye, holding it steady in space as the head completes its motion (5, 6).
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12. For model equations and predictions see D. Tweed, *ibid.* **77**, 654 (1997). In this model, eye and head are driven by two separate feedback loops to goal positions defined in space-fixed coordinates.
13. The loss of acuity caused by horizontal and vertical image slip depends on the spatial frequency of the image, which means that regions with a lot of fine detail are usually degraded more than coarse patches; see R. H. S. Carpenter, *The Movements of the Eyes* (Pion, London, 1988). Something analogous likely holds for the effects of torsional image slip on orientation detectors; radially oriented contours are degraded more than circumferential contours, so that the spokes of a spinning wheel are hard to make out, while the rim is clear.
14. J.-R. Duhamel, C. Colby, and M. Goldberg [*Science* **255**, 90 (1992)] reported that some visual cells in the parietal cortex adjust their receptive fields in anticipation of gaze shifts. Such cells will, for example, shift their receptive fields to the right immediately before rightward eye movements. Based on our results, one might also expect to find cells that adjust their receptive fields in the torsional dimension. For instance, an orientation-sensitive cell that normally responds best to horizontal lines may prefer CW-rotated lines in the final milliseconds before a CW gaze shift.
15. Advantages of rezeroing torsion are that the eye muscles probably require less force to hold an eye position near Listing's plane and that the eye, at the

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center of its torsional range, is optimally placed for the next gaze shift, which may go either CW or CCW [see K. Hepp, *Vision Res.* **35**, 3237 (1995) and D. Tweed, *ibid.* **37**, 1939 (1997)].

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