Visuo-Vestibular Eye Movements

Infantile Strabismus in 3 Dimensions

Michael C. Brodsky, MD

Infantile strabismus is accompanied by latent nystagmus, primary inferior oblique muscle overaction, and dissociated vertical divergence. If we examine the evolutionary underpinnings of these ocular rotations, we can construct a unifying mechanism for the sensorimotor abnormalities that arise in humans with infantile strabismus. Latent nystagmus, primary inferior oblique muscle overaction, and dissociated vertical divergence correspond to visual balancing reflexes that are operative in lateral-eyed animals in yaw, pitch, and roll, respectively. In humans with infantile strabismus, these subcortical visual reflexes are reactivated by a physiologic imbalance in binocular visual input, which resets central vestibular tone in 3-dimensional space. These visual reflexes reveal the evolutionary role of the eyes as sensory balance organs that can directly modulate central vestibular tone. Latent nystagmus, primary oblique muscle overaction, and dissociated vertical divergence should be reclassified as visuo-vestibular eye movements.

Arch Ophthalmol. 2005;123:837-842

1. THE PROBLEM IS GRAVITY

Why is symmetry ubiquitous in the animal kingdom? More specifically, what is the evolutionary origin of the bilateral symmetry that dictates that we have 2 eyes, ears, arms, and legs situated equidistant from the midline? The problem of symmetry in biological systems is a complex subject of ongoing study. One of the evolutionary functions of biological symmetry is balance. Because of the earth's gravitational field, survival requires that animals maintain vertical orientation. An animal that falls tends to get eaten. For living organisms, gravity necessitates balance. Because physical symmetry promotes balance, biological symmetry is an important part of nature's solution to the problem of gravity.

2. BILATERALLY SYMMETRICAL ORGANS FUNCTION AS BALANCE ORGANS

The evolution of bilaterally symmetrical organs situated equidistant from the sagittal plane promotes balance by virtue of physical weight alone. Our 2 lungs, when inflated with air, become ballast in water. But many bilateral structures also func-
tion as physiologic balance organs. While it is axiomatic that our 2 labyrinthine superintend balance, other bilateral organs modulate balance in different ways. Our 2 cerebral hemispheres each control motor tone in the contralateral limbs. Our 2 cerebellar hemispheres clearly control balance. Even the 2 kidneys have been shown to function in part as balance organs.7

3. LATERAL EYES ARE SENSORY BALANCE ORGANS

Our ancestral environment is characterized by 2 physical constants: light from the sky above and gravity from the earth below.8 Although the sun is the source of light, it adds little to the overall brightness of the sky. Throughout evolution, the bright sky has served as a space-stable luminance hemisphere.8 Because light comes from above, when the eyes are laterally positioned, vertical alignment is signaled by equal luminance to the 2 eyes. Evolution has programmed this visual cue into our balance system to optimize survival.

While it is axiomatic that our 2 labyrinths keep us informed of our relation to our gravitational position (a static otolithic system) and movement (a dynamic semicircular canal system), our 2 eyes subserve the same function because an animal cannot rely solely on vestibular input during momentary physical perturbations by wind and waves.9 The striking correspondence of eye-muscle position to semicircular canal and extracochlear muscle orientation permits the eyes and ears to subserve balance in lockstep. As summarized by Duke-Elder,10 . . . the control of the movements of living animals, both plants and animals, by light is a fundamental function of great phylogenetic age, preceding the acquirement of vision and, indeed, leading directly to its development. The association of the functions of equilibration and orientation with the visual system of higher animals is in every sense basic.

4. PRIMITIVE REFLEXES ARE RESURRECTED WHEN NORMAL NEURODEVELOPMENT FAILS TO OCCUR

Many primitive reflexes that promoted survival in the ancestral setting lose their beneficial function as evolution proceeds.11,12 With progressive encephalization, newer cortical reflexes are grafted onto older subcortical reflexes, which persist in latent form even when they no longer serve a useful function.13,14 Abnormal neurodevelopment in infancy is associated with a persistence of numerous subcortical reflexes (Table 1).15 In pediatric neurology, these primitive reflexes are among the clinical signposts of abnormal neurodevelopment.15 In pediatric ophthalmology, these echoes from our visual ancestry signal maldevelopment of cortical binocular vision.

In the developing visual system, monocular nasotemporal asymmetry is perhaps the quintessential example of a visual reflex in which ontogeny recapitulates phylogeny. Nasotemporal asymmetry refers to a monocular horizontal optokinetic response that is brisk in the nasal direction and poor or absent in the temporal direction.16 This directional optokinetic bias is normal in lateral-eyed animals and in human infants within the first 6 months of life. Humans with infantile strabismus retain a nasotemporal asymmetry that provides the monocularly driven horizontal movement bias for latent nystagmus.16

5. OCULAR MOTOR INCURSIONS OPERATE AS VISUAL BALANCING REFLEXES IN LATERAL-EYED ANIMALS

Primitive visual reflexes rely on a dissociated form of binocular vision between the 2 laterally placed eyes, which has been superseded by cortical binocular vision in humans.9 Humans experience frontal binocular vision with forfeiture of peripheral vision in exchange for cortical fusion and stereopsis. Infantile strabismus recreates the dissociated binocular condition that allows lateral-eyed animals to process dissociated luminance and visual input from each eye with little or no binocular overlap. Infantile strabismus effectively disables the newer cortical binocular system and unveils the primitive visual reflexes that have been inscribed into our primitive ocular motor control system.18,16

The resurrection of these primitive visual reflexes generates a triad of ocular movements that have come to define infantile strabismus. This symphony of eye movements reveals each of the primitive visual reflexes that use dissociated binocular visual input to maintain physical orientation in 3-dimensional space.

Latent nystagmus corresponds to the optokinetic component of ocular rotation that is driven monocularly by nasal optic flow during a turning movement of the body in lateral-eyed animals.16 When infantile esotropia disrupts the establishment of binocular visual connections, visual input from the fixating eye to the contralateral nucleus of the optic tract evokes a counterrotation of the eyes that corresponds to a turning movement of the body toward the object of regard. The clinical expression of this visual reflex is also evident in the monocular nasotemporal asymmetry to horizontal optokinetic stimulation that characterizes infantile strabismus.16

Dissociated vertical divergence corresponds to the dorsal light reflex that has been observed in fish and...
other lateral-eyed animals when unequal luminance to the 2 eyes evokes a body tilt or vertical divergence of the eyes toward the side with greater luminance. In humans, dissociated vertical divergence is a visual balancing reflex that uses weighted binocular visual input to orient eye position to the perceived vertical (Figure 1). The exaptation of a cycloversional movement into the human dorsal light reflex permits active modulation of perceived visual tilt when the eyes are frontally positioned.

Primary inferior oblique muscle overaction corresponds to a similar dorsal light reflex that is induced in fish when a forward or backward shift in overhead luminance evokes an ipsidirectional body pitch or torsional rotation of the eyes backward to reorient the body with respect to the light. These binocular torsional rotations of the eyes constitute a physiologic form of primary oblique muscle overaction that can be induced by altering binocular visual input. In humans, a forward or backward rotation relative to overhead light sends excitatory innervation to each of the elevators or each of the depressors. Because the vestibular system segregates innervation to its target extraocular muscles, the vertical actions of the human oblique muscles summate in adduction with those of the rectus muscles to produce the innervational overelevation of the adducting eye that defines primary inferior oblique muscle overaction. The fundamental association of primary oblique muscle overaction with early loss of binocular vision in humans suggests that the brain registers abnormal binocular visual input as forward rotation.

6. PRIMITIVE VISUAL REFLEXES ARE EVOKED BY A PHYSIOLOGIC IMBALANCE IN BINOCULAR VISUAL INPUT

Most patients with infantile esotropia have no neurologic disease. From where do these involuntary ocular rotations arise? Stereotypical eye movements that do not fit any paradigm must come from somewhere. As stated by Keiner, “Nothing comes from nothing.” The source of these dynamic intrusions has eluded us for the simple reason that they arise from a physiologic imbalance rather than from a neurologic lesion. They are harmonics of our earlier orchestration that bubble to the surface when they are not superseded by cortical binocular reflexes.

Just as physiologic vestibular movements reflect the degree of unbalanced labyrinthine input, the size of these eye movements are proportional to the degree of binocular visual imbalance, which can fluctuate depending on momentary cortical suppression of either eye. Because the eye movements of infantile strabismus are calibrated by weighted binocular visual input, they increase in proportion to the disparity of visual input from the 2 eyes.

7. LATENT NYSTAGMUS, PRIMARY OBLIQUE OVERACTION, AND DISSOCIATED VERTICAL DIVERGENCE ARE VISUO-VESTIBULAR EYE MOVEMENTS

In lateral-eyed animals, visual and labyrinthine input are pooled together within the central vestibular system to establish central vestibular tone. Based on momentary fluctuations in bilateral input, the central vestibular system constantly modulates eye position and body position to maintain physical orientation in 3-dimensional space. Vestibular input predominates over visual input, but both systems are integrated at the level of the vestibular
nucleus to maintain balance. In infantile strabismus, binocular visual imbalance alone can alter central vestibular tone. Because input to the vestibular nucleus can be directly driven by the balance of visual input from the 2 eyes, this unique form of central vestibular imbalance does not require that the central nervous system receive an imbalance of labyrinthine input. It is as if infantile strabismus transforms the 2 eyes into physiologic vestibules. These unique eye movements are visuo-vestibular in origin.

8. VISUO-VESTIBULAR EYE MOVEMENTS ARE GENERATED BY SUBCORTICAL CENTRAL VESTIBULAR PATHWAYS

In the absence of binocular cortical development, the system defaults to a subcortical control system in which the central vestibular system is the gyroscope that sets postural tonus to the extraocular muscles. These subcortical motor pathways receive both afferent input from the optic nerves and efferent input from the visual cortex. As with the pupillary light reflex, however, cortical input can modulate these subcortical reflexes. Thus, voluntary or involuntary suppression of 1 eye can activate latent nystagmus and dissociated vertical divergence.

The clinical expression of these subcortical reflexes in the setting of infantile strabismus reflects the evolution of a hierarchical visual system in which cortical binocular vision can hold our subcortical reflexes in check. In infantile strabismus, subcortical visual reflexes are reactivated because the system reverts to a dissociated binocular system.

9. VISUO-VESTIBULAR EYE MOVEMENTS ARISE FROM A CENTRAL VESTIBULAR IMBALANCE THAT DISSOCIATES CLINICALLY INTO 3 DISTINCT PLANES

Vestibular eye movements are governed by the anatomical orientation of the labyrinths and occur in 3 major head-referenced planes. Yaw rotation occurs around the z or vertical axis, pitch rotation occurs around the y or interaural axis, and roll rotation occurs around the x or nasal-occipital axis (Figure 2). While vestibular eye movements are driven by sensory input from the 2 labyrinths, visuo-vestibular eye movements are driven by visual input from the 2 eyes. In infantile strabismus, the 2 eyes function as physiologic vestibules that can directly modulate central vestibular tone in a complementary way to a labyrinthine imbalance. These visuo-vestibular eye movements generate latent nystagmus in the yaw plane, primary oblique muscle overaction in the pitch plane, and dissociated vertical divergence in the roll plane (Table 2).

Ultimately, all 3 visuo-vestibular eye movements are clinical expressions of a visually induced imbalance in central vestibular tone, as evidenced by the fact that they manifest as rotations in the same head-referenced planes as vestibular eye movements, which are governed by the orientation of the anatomical components of the 2 labyrinths. One could geometrically display any variable combination of these 3 movements as a single vector in 3-dimensional space based on the size and direction of each movement in its corresponding plane.

Because these visuo-vestibular movements correspond to vector components of a single central vestibular imbalance in 3-dimensional space, it is not surprising that their clinical features can overlap. Thus, dissociated vertical divergence incorporates a vertical latent nystagmus, revealing the shared common origin of these movements. Clinically, primary oblique muscle overaction and dissociated vertical divergence often summate to produce an admixture of overelevation in adduction. Similarly, latent nystagmus incorporates vertical and torsional movements that overlap those of dissociated vertical divergence.

Each plane of rotation imparts unique clinical features to its visuo-vestibular response. The fact that latent nystagmus is a dynamic imbalance while primary oblique muscle overaction and dissociated vertical divergence are tonic imbalances probably reflects the natural head and body movements that occur in the 3 orthogonal planes of physical space. During navigation, an animal may turn its head and body back and forth rapidly, but pitch or tilt movements tend to be slow and sustained. Our evolutionary program-
mals. These visual reflexes subserve balance by enabling the animal to leverage fluctuations in binocular visual input to maintain postural orientation.

By disrupting the development of frontal binocular vision, infantile strabismus permits our primitive visual reflexes to “bubble to the surface.” The resulting ocular intrusion movements reflect an imbalance of binocular visual input in 3 planes of physical space. These overlapping visuo-vestibular eye movements can be deconstructed clinically into their 3 dimensions, corresponding to yaw, pitch, and roll. The symphony of binocular movements that accompanies infantile strabismus is a necessary expression of our primitive heritage that impelled them into being. At a higher level, these movements reveal the wisdom of antiquity by reminding us how survival in a gravitational world once necessitated the evolution of a physical symmetry and its co-orchestration at both anatomical and physiologic levels.

Infantile strabismus provides a natural experiment to uncover the primitive visual reflexes that lie buried within us. These visual reflexes are humanity’s umbilical cord reaching back to a time when the 2 eyes functioned together as sensory balance organs. In infantile strabismus, dissociated binocular vision remains the fulcrum on which the visuo-vestibular system teeters. The beauty of infantile strabismus is that each piece of our visual ancestry is laid out in bold relief. We see unraveled before us a blazing display of the primitive visual reflexes that were once necessary to maintain physical orientation in 3-dimensional space.

More importantly, these preternatural eye movements provide a unique glimpse into a larger universal system of physical order. As eloquently stated by the 19th-century English author Thomas de Quincey:

Even the articulate or brutal sounds of the globe must be all so many languages and ciphers that somewhere have their own grammar and syntax; and thus the least things in the universe must be secret mirrors to the greatest.34

10. VISUAL REFLEXES ARE STEREOISOMERS OF VESTIBULAR REFLEXES

For each plane of head rotation, visuo-vestibular eye movements generate a 3-dimensional rotation of the eyes that is a mirror image of its corresponding vestibulo-ocular imbalance. Thus, latent nystagmus is the visual counterpart to horizontal vestibular nystagmus, primary oblique muscle overaction is the mirror-image visual counterpart to bilateral alternating skew deviation, and dissociated vertical divergence is the visual counterpart to the ocular tilt reaction of which skew deviation is a component. For unity to exist under physiologic conditions, visuo-vestibular eye movements must complement vestibulo-ocular movements so that their additive functions summate to 0 in each plane. This central yoking of binocular and bilabyrinthine sensory input within the central vestibular system underscores the role of symmetry in our evolutionary design and explains the close geometric correspondence between the semicircular canals and the extraocular muscles.33 The system fits together nicely.

CONCLUSIONS

The eye movements of infantile strabismus are harmonics of our earlier orchestration; echoes of our visual ancestry. Visual analogues of latent nystagmus, dissociated vertical divergence, and primary oblique muscle overaction are found in the normal visuo-vestibular eye movements of lateral-eyed animals. These visual reflexes subserve balance by enabling the animal to leverage fluctuations in binocular visual input to maintain postural orientation.

By disrupting the development of frontal binocular vision, infantile strabismus permits our primitive visual reflexes to “bubble to the surface.” The resulting ocular intrusion movements reflect an imbalance of binocular visual input in 3 planes of physical space. These overlapping visuo-vestibular eye movements can be deconstructed clinically into their 3 dimensions, corresponding to yaw, pitch, and roll. The symphony of binocular movements that accompanies infantile strabismus is a necessary expression of our primitive heritage that impelled them into being. At a higher level, these movements reveal the wisdom of antiquity by reminding us how survival in a gravitational world once necessitated the evolution of a physical symmetry and its co-orchestration at both anatomical and physiologic levels.

Infantile strabismus provides a natural experiment to uncover the primitive visual reflexes that lie buried within us. These visual reflexes are humanity’s umbilical cord reaching back to a time when the 2 eyes functioned together as sensory balance organs. In infantile strabismus, dissociated binocular vision remains the fulcrum on which the visuo-vestibular system teeters. The beauty of infantile strabismus is that each piece of our visual ancestry is laid out in bold relief. We see unraveled before us a blazing display of the primitive visual reflexes that were once necessary to maintain physical orientation in 3-dimensional space.

More importantly, these preternatural eye movements provide a unique glimpse into a larger universal system of physical order. As eloquently stated by the 19th-century English author Thomas de Quincey:

Even the articulate or brutal sounds of the globe must be all so many languages and ciphers that somewhere have their own grammar and syntax; and thus the least things in the universe must be secret mirrors to the greatest.34

Table 2. Planar Components of Central Vestibular Disease

<table>
<thead>
<tr>
<th>Plane</th>
<th>Visuo-Vestibular Imbalance</th>
<th>Vestibular Counterpart (Peripheral vs Central)</th>
<th>Vestibular Ocular Reflex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw</td>
<td>Latent nystagmus</td>
<td>Horizontal vestibular nystagmus (peripheral)</td>
<td>Dynamic</td>
</tr>
<tr>
<td>Pitch</td>
<td>Primary inferior oblique</td>
<td>Bilateral alternating of skew deviation (central)</td>
<td>Tonic</td>
</tr>
<tr>
<td>Roll</td>
<td>Dissociated vertical divergence</td>
<td>Skew deviation (central)</td>
<td>Tonic</td>
</tr>
</tbody>
</table>

Funding/Support: This article was supported in part by unrestricted grants from the Research to Prevent Blindness (New York, NY) and the Pat and Willard Walker Eye Research Center, Harvey and Bernice Jones Eye Institute, University of Arkansas for Medical Sciences (Little Rock).

REFERENCES

9. Brodsky MC. Dissociated vertical divergence: a