Minnesota Brain Injury Alliance
Annual Conference: Vestibular Post Concussive Symptoms

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Minnesota Functional Neurology and Chiropractic
Topics we will cover

- Vestibular Nerve Anatomy and Physiology
- Vestibular Nuclei and Subnuclei
- Vestibulocerebellum Anatomy and Physiology
- Velocity Storage Anatomy and Physiology
  - Rotational VOR Fundamentals
  - Translational VOR Fundamentals
- Vestibulospinal Fundamentals
- Extra-Vestibular Postural Responses
- Vestibuloautonomic Fundamentals
- Vestibular Contribution to Everyday Function
  - Bedside Functional Examination
  - Clinical Thought Process
- Chiropractic and Cervical Spine Vestibular Integration
- Brain Maps
Vestibular disorders following different types of head and neck trauma

Ognyan I. Kolev, MD, PhD,a,b and Michaela Sergeeva, MD, PhDa

In conclusion, the present review provides an overview of the various mechanisms underlying the vestibular disorders that follow head trauma. They can be due to organic, structural or substructural (microscopic) damage localized at different vestibular levels, from the labyrinth to the cortical regions; they can also involve non-vestibular structures, such as neck proprioreceptors, whose signals integrate with the vestibular afferentation, as well as humoral mechanisms. They can also be psychogenic, functional disorders. Thus, vestibular examination and other related tests are very useful for establishing the site, pathogenesis and severity of traumatic vestibular disorder. Such information will improve the results of therapy.
Vestibular disorders following different types of head and neck trauma

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There are several types of post-traumatic dizziness and its pathogenesis remains controversial (Brandt, 1999; Shepard, 2013; Tuohimaa, 1978). Likewise, opinions on the important factors to evaluate are numerous, but in general there are three schools of thought. One considers dizziness, as well as the other symptoms of the post-traumatic syndrome, to be of psychogenic origin; according to a second school of thought, post-traumatic dizziness is exclusively of organic origin; finally, the third school emphasizes the importance of factors of both types (Brandt, 1999). Head trauma can directly damage the vestibular organ or vestibular nerve, as well as the brainstem and the visual and oculomotor pathways, and lead to vestibular disorders (Allison and Fuller, 2000). Unfortunately, associated anxiety and secondary gain factors make it difficult to distinguish clearly between organic and psychogenic mechanisms (Brandt, 1999).
The frequency of dizziness and disequilibrium following head trauma is about 40–60% among non-hospitalized patients (Gannon et al., 1978). Even in cases of mild head trauma dizziness was reported to persist for at least two years in 18% of patients (Cartlidge, 1978). These figures signify that there is a common etiology for a heterogeneous collection of peripheral and central vestibular disorders (Brandt, 1999). According to Kushner (1998), the organically conditioned dizziness that occurs after head trauma is usually peripheral rather than central in origin. The late onset of the symptomatology can be explained by the slow degeneration that sets in after concussion (Brandt, 1999). The most frequent peripheral form of vertigo after head trauma is benign paroxysmal positional vertigo (PPV), thought to be due to dislodgement of otoliths from the macula of the utricle (Brandt, 1999; Shepard, 2013). Clinical experience and the most recent literature show that post-traumatic PPV (canalolithiasis) is usually unilateral, and less frequently bilateral. However, bilateral PPV is recognized to have a post-traumatic etiology. When canalolithiasis is bilateral, paroxysmal vertigo and related nystagmus are more pronounced on one side. The symptoms may persist for between a day and up to more than a year (Shepard, 2013).
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Vestibular dysfunction after labyrinthine concussion has often been ascribed to unilateral microscopic hemorrhages in the labyrinth (Davies and Luxon, 1995). Labyrinthine concussion is often manifested by vertigo, nausea and/or vomiting, but the vestibular examination focuses on pathological nystagmus that occurs spontaneously and is exacerbated during rapid head movements. Generally, labyrinthine concussion resolves through adaptation over a period of weeks or months, a process known as vestibular compensation (Shepard, 2013). While vestibular suppressants dramatically improve the symptoms during the early period after trauma, they generally delay compensation and subsequently recovery (Shepard et al., 1990).
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Vestibular testing of patients with head trauma shows that head trauma may damage the peripheral and central vestibular structures, simultaneously or separately (Brandt, 1999). Many authors support the hypothesis that traumatic brain injury with vestibular symptoms affects both the peripheral and central vestibular structures. A recent study on patients after mild head trauma and subsequent vestibulopathy compared radiological findings and clinical assessment — this focused on reduction of cognitive functions, severity of symptoms and time to recovery — in these patients. They were shown to have significant axonal impairment irrespective of the prevailing peripheral vestibular symptoms. These findings support the hypothesis that post-traumatic vestibulopathy has a central axonal injury component (Alhilali et al., 2014).
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Central vestibular syndromes are mostly due to concussion of vestibular nuclei or central vestibular pathways. Direct traumatic damage to the brainstem or cerebellum may be followed by the occurrence of imbalance and transitional vertigo (Shepard, 2013). All the parts of the brainstem and the cerebellum can be affected, but the mesencephalon somewhat more often (Brandt, 1999). Symptoms of a central origin may include nausea with non-positional vertigo and imbalance (Kushner, 1998).
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In whiplash injuries, dizziness and vertigo are the most probable symptoms (changes in vestibular function); other pathogenetic explanations are based on neuromuscular (Gray, 1956) and neurovascular mechanisms (Weeks and Travelli, 1955), overexcitation, or damage of the cervical and/or lumbar proprioceptors (Hinoki, 1985; Nacci et al., 2011). Acceleration forces associated with traumatic injury probably loosen the otoconia; this leads to unequal otolith masses on the two sides, thus causing a temporary disturbance of spatial orientation (Brandt, 1999). A comparative otoneurological study was conducted in two groups of dizzy whiplash patients: patients with dizziness after pure whiplash injury and those with minor injury associated with whiplash. This study showed that there were only a few cases in which whiplash caused central or peripheral vestibulopathy, which was more probable after minor head injury associated with whiplash. Impaired postural control in these patients was more often related to cervical proprioceptive disorders that could be mistaken for a vestibular symptom (Nacci et al., 2011).
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There are some non-vestibular causes of dizziness occurring after traumatic brain injury. Orthostatic hypotension, as a cause for dizziness, may be related to physical deconditioning, medullary injury or be a side effect of medications such as some antihypertensives, analgesics or beta blockers. Other symptomatic drugs for post-concussion syndrome (e.g., benzodiazepines, diuretics and anti-convulsants) may also lead to sensations of dizziness (Daroff and Carlson, 2005). Dizziness may be related to pre-existing conditions such as neurological disease, labyrinthopathy, cardiac disease or diabetes. One frequent complication of traumatic brain injury, i.e. hyponatremia (Agha et al., 2004; Harrigan, 1996; Zafonte and Mann, 1997), can cause dizziness or orthostatic hypotension (Armstrong, 2004; Harrigan, 1996; Taylor et al., 1995). When investigating post-traumatic vertigo and dizziness it is useful to apply the specialized vestibular tests, for example, checking for spontaneous nystagmus with and without Frenzel’s glasses, and for positional and positioning nystagmus, the head-shaking test, the Halmagyi test (the head-thrust test), and the vestibular bithermal caloric test. It has been shown that posturographic examination with eyes open and closed is useful for dynamic monitoring of patients in the post-traumatic period. In addition, it has been proven that balance control is related to the vestibular-spinal reflex and cervical proprioception in whiplash patients (Nacci et al., 2011).
Symptoms of Concussion

• Dizziness/ loss of balance
• Sensitivity to light and noise
• Confusion or head fog
• Dazed appearance
• Ringing in the ears

• Fatigue
• Headaches
• Sleep disturbance
• Nausea
• Poor concentration
• and memory loss
• Slow or slurred speech
How Do Concussions Occur? How Often?

• Concussions occur as a result of impact through linear and rotational forces to the brain.
• There is currently no known amount of force that is directly linked to causing a concussion.
• 1.6 to 3.8 million concussions occur in sports and recreational activities annually. These numbers are vastly underestimated due to underreporting.
What Happens as a Result of Concussion?

- Loss of postural control
- Poor balance
- Dizziness
- Poor cognition (brain fog)
Loss of Postural Control after Concussion
Poor Balance after Concussion

• Balance impairment, or postural instability, is a common source of long term physical disability after a concussion.
• There is an association between early loss of balance after concussion and delayed functional recovery.
How MFNC Assesses Loss of Balance

- Computerized Posturography: Testing safely and effectively assists the diagnosis of balance impairments
- Provides quantitative data to track changes over time and/or assess the efficacy of treatment interventions
- Similar to findings in mild concussion, vestibular dysfunction appears to underlie postural instability after severe concussion
Recovery of Balance

• Without proper assessment of balance control, a concussed athlete may return to play not fully recovered. This can lead to further injury.

• Proper assessment and treatment are key to an athlete’s full, long term recovery.

• Loss of balance was more pronounced in the Anterior-Posterior direction (front to back).
Dizziness after Concussion

- Dizziness has been reported within the first few days after injury, in up to 80% of TBI cases.
- Dizziness is a very non-specific term and can be placed into four broad categories:
  1. Vertigo
  2. Pre-syncopal lightheadedness
  3. Multisensory dizziness
  4. Psycho-physiologic dizziness
Poor Cognition (Brain Fog) after Concussion
Proper Comprehensive Assessment and Management of Athletes with Sport Concussion

• The brain is a complex and complicated organ. No two concussions are the same and, consequently, no two treatment programs can be identical.

• Athletes with concussion rapidly develop short-term impairment of neurologic function; among those, 80-90% resolve spontaneously within the first ten days, although the recovery timeframe may be longer in children and adolescents than in adult.

• However, a small percentage of patients, experience prolonged, physical, behavior, neuropsychological, and/or personality changes frequently termed post-concussive syndrome (PCS).
POST CONCUSSION SYNDROME

- headaches
- fatigue
- injury
- trauma
- risk
- head
- disorder
- chronic
- football
- dizziness
- symptoms
Long-Term Effects after Concussion

• An isolated concussion has systemic consequences for several organs, including cardiovascular disorders, autonomic abnormalities, intestinal dysfunction, leaky gut and motility problems, and more.

• Compelling data from several studies demonstrate that a history of concussion is one of the strongest epigenetic risk factors for Alzheimer’s Disease and may accelerate its onset.
Additional Findings with Post-Concussive Syndrome

- Poor dual tasking (performing two tasks at once)
- Improper gait (walking)
- Impaired eye movements; influencing balance dizziness, cognition, depression, headaches, vestibular pathology
- Vestibulo-ocular monitoring as a predictor of outcome after severe concussions
- Immune system dysregulation
What Does Functional Neurology Offer in Terms of Healing and Treatment after Concussion?
MFNC System

1. Does the patient know where their head is in relation to gravitational inputs?
2. Do they have stable autonomics?
3. Tonic Vestibular stability and static positional stability before movement.
4. Activation of Vestibular Only Systems
5. Passive Vestibular and cerebellar feedback- supine, seated, standing, movement
6. Cervical Spinal Integration
7. Address Specific cortical regions and mapping
8. Integrate Visual, Vestibular and Proprioceptive
9. Active re integration into gravity
10. Contextual Training
Work with the Circuitry of the Nervous System

Utilizing Functional Neurology
How We Can Help

We investigate how the nervous system is functioning, as opposed to mere black and white pathology

• Ablative vs. physiological lesions

Unique questions we ask ourselves:

• What neural pathways and structures are viable?
• What can we do to optimize the function of these structures?
• How can we best improve the lives of our patients by enhancing the overall functioning of their nervous system?
Observation of the small details is key:

We break down where the issue is in the brain and treat accordingly.
MFNC: What We Offer

• In-depth Chiropractic Neurological examination
• (VOG) Testing
• Saccadometry
• Computerized Platform Posturography
• Interactive Metronome
• Dynavision D2 assessment
Angular VOR Substrate

Vestibular nuclei (8th) are connected to the oculomotor nuclei

- 3rd & 4th – to move the eyes vertically and torsionally
- 6th & 3rd – to move the eyes horizontally

Keep vision stable
Saccadometry
DIAGNOSTICS

Baseline Testing:

- Dynavision D2™ Assessment
VOG Analysis
“When a reporter asked the famous biologist JBS Haldane what his biological studies had taught him about God, Haldane replied, “The creator, if he exists, must have an inordinate fondness for beetles,” since there are more species of beetle than any other group of living creatures.

By the same token, a neurologist might conclude that God is a cartographer. He must have an inordinate fondness for maps, for everywhere you look in the brain maps abound.”
A recent wave of discovery has quite clearly revealed that the brain retains its ability to adapt to its ever changing environment throughout life.

It is becoming clear to neuroscientists how important it is for our brains to maintain an accurate and up to date inner map, of the location of our muscles and joints in 3D space and relative to each other, and how detrimental a faulty inner map can be for an individual.
You cannot really be certain that any of your sensory experiences accurately reflect what is going on within and around you.

Your brain will not provide you with an exact translation of what its sensors tell it, but it will integrate this sensory information with its own expectations from the past, its intent for the immediate future, and in the context of the current situation.

So, in reality, there is no one reality. your own inner reality may not reflect what is really going on in and around you. But regardless of its accuracy, your inner reality is very real to you.
Brain Maps

For almost a century, the presence of “maps” in mammalian sensory cortices has been recognized.

The first clear demonstration was Inouye’s mapping of human visual cortex from lesion-induced scotoma in 1909.

Regarding the tactile modality, it was known long ago that both primary and secondary somatosensory cortical regions (S1 and S2) possess a map-like organization.
Brain Maps

The sum total of your numerous, flexible, morphable body maps gives rise to the solid-feeling subjective sense of “me-ness” or your embodied self and to your ability to comprehend and navigate the world around you.

All of your other mental faculties such as vision, hearing, language and memory are all dependent on this embodied feeling of self.

Developmentally speaking, it would be impossible to become a thinking, self-aware person without these body maps.
Sensory Integration

Many functions involve the cooperation of vestibular, visual and somatosensory/proprioceptive inputs.

One becomes aware of vestibular and other proprioceptive sensations only when they are in conflict with vision or the expectations arising from past experience.
Every point on your body, each internal organ and every point in space out to the end of your fingertips, is mapped inside your brain.

Your ability to sense, move and act in the physical world arises from a rich network of flexible body maps distributed throughout your brain.

Maps which can grow, shrink and morph to suit your needs.
In everyday life, we experience the space around us as a unitary and seamless whole. The brain constructs various functionally distinct representations of space such as near, peripersonal space compared to far, extrapersonal space.

Peripersonal space defines the region of space immediately surrounding our bodies in which objects can be grasped and manipulated.

Extrapersonal space refers to the space beyond grasping difference, in which exploratory eye movements occur.
A special mapping process connects this peripersonal space to your limbs and body.

The maps that encode your physical body are connected directly, immediately, personally to a map of every point in that space and also map out your potential to perform actions in that space.

Your self does not end where your flesh ends, but blends with the world, including other beings.

Brain cells that normally represent space no farther out than your fingertips can expand their fields of awareness outward depending on the environmental context.
Peripersonal space representation is not only pivotal for the sensory guidance of actions, but it is also dynamically modulated by voluntary actions themselves, so that performing a reach-and-grasp movement enhances crossmodal, visual-tactile interaction in the space around the acting hand, immediately before the execution.
**External Space**

Peripersonal space is elastic and like an amoeba it expands and contracts to suit your goals.

Your brain maps the space beyond your body when you are using tools or objects.

If you take hold of a hockey stick and tap it on the ground. As far as your brain is concerned, your hand now extends to the tip of that stick.

Its length has been incorporated into your personal space.

This is one reason why people who are blind can learn to walk much more effectively with a walking stick as they integrate a larger peripersonal space.

If you are driving a car your peripersonal space expands to include the car, from fender to fender, from door to door and from tire to roof.
In addition to the classical five senses, all vertebrates possess the ability to detect motion of the head and body in space through a set of specialized sensory organs located in the inner ear.

The vestibular system is fundamental for navigation and spatial orientation.

The various components of self-motion, head rotations and translations, are transduced by two set of vestibular sensors, the semicircular canals and the otolith organs, respectively, as well as the visual system.
Vestibular System

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Reference Frames

Peripheral vestibular neurons use head-fixed reference frames.

In contrast, central vestibular-related neurons can integrate signals from two or more sensory channels to transform their reference frames to be body-centered, eye-centered, or world-centered.
Vestibular Integration


• Vestibular system contributes to:
  – Oculomotor system — Postural system
  – Spatial perception
  – Spatial navigation
  – Body representation — Attention
  – Memory
  – Mental imagery — Social cognition.
Redundant multimodal inputs are integrated by the central processor, the vestibular nuclear complex, which generates motor commands to drive the eyes and body.

The system is normally very accurate.

To maintain accuracy, the vestibular system is monitored and calibrated by the cerebellum.
Vestibular System

The vestibular system contributes to equilibrium, in particular while walking on uncertain or slippery terrains.

The vestibular system drives a gaze stabilization reflex called the vestibulo-ocular reflex (VOR), which maintains a sharp vision when moving the head.

The vestibular system allows tracking head and body position in space when performing complex sequence of movements.

Unlike with other senses, one is usually not aware of the existence of “vestibular perception”.
Vestibular System

The vestibular system projects to many areas of the cerebral cortex but unlike other sensory systems there is no primary vestibular cortex that only receives vestibular signals.

All cortical neurons that receive vestibular signals also receive other sensory signals, particularly visual and somatosensory.
Vestibular System

The vestibular system contributes to several levels of nervous system function, including reflexes designed to keep vision clear during head motion or to maintain blood pressure when one quickly goes from supine to an erect posture, more complicated strategies required in maintaining an upright posture, and higher perceptual functions involved in our conscious awareness of our position in our environment and our ability to navigate through it.

Even seemingly simple reflexes are far from simple, as they involve the integration of information from several sensory channels, are subject to context-specific modifications, and are continually being recalibrated using mechanisms of plasticity, similar to those involved in the learning and refining of other motor skills.

The vestibular system contributes to most everyday activities that involved self-motion or motion of the environment.
Otolithic Integration

The acceleration of gravity is the fundamental reference for your brain to use as a baseline in developing your standards for measuring time, space and energy.

The acceleration of gravity and the unchanging direction of the force of gravity also is important in allowing your brain to develop a three dimensional sense of direction in space, it serves as the common denominator for the integration of all of the various sensory.
Intuitively, sensing gravity effects should be a trivial problem for a complex nervous system such as our own.

Our nervous system is computationally high-powered, being endowed with approximately $10^{11}$ neurons interconnected via approximately $10^{15}$ synapses.

All axons pieced together would cover the distance between the Earth and the Moon (about 400,000 km).
Gravity

One would assume that we are able to monitor gravity directly by means of our sensory systems, but this is not the case.

Gravity effects are only extrapolated indirectly by the brain by combining multisensory information with internal models, that is, with neural processes which mimic a physical event.
Sensing and coping with gravity is crucial for space perception, control of upright posture, and generation of movements.

Gravity provides a unique reference axis to which we can anchor body orientation and monitor orientation changes.

Gravity effects on limb and body movements are two-sided, insofar as gravity acts both as a perturbing force that must be counteracted to avoid falling down and as a facilitating force which allows walking and running via the ground contact forces.
An apparently simple problem such as that of monitoring gravity effects on our body and on the external environment is in fact computationally very demanding, even for a high-powered brain such as that of primates.

Measurements derived from individual sensory organs are often ambiguous and noisy.

However, the combination of multisensory signals (visual, vestibular, proprioceptive, and visceral) and the reliance on internal models of physics yield estimates which are very accurate under normal conditions, but which can fail badly under anomalous conditions.

Central processing of multisensory information and internal models occurs in a widely distributed network of cortical and subcortical regions.

The extensive integration of sensory and motor information in this network makes gravity-related information available to many vital functions of the organism.
Z-Axis Rotation

If an individual rotates around the z-axis in a barbecue roll fashion at a constant velocity, the activity of the angular acceleration-sensitive semicircular canals will decay to baseline in less than a minute after completion of the acceleration phase.

The otolith organs are activated by linear acceleration and are being continually reoriented in relation to the direction of gravity and thus stimulated throughout the rotation period.
Plantar Afferentation in Oculomotor Control

The central nervous system uses afferentation from the feet for both postural and ocular vergence control.

Vibration of extrinsic foot muscles gives rise to an impression of the displacement of a visual target.
• Vergence accuracy has been shown to be best during body movements.
• Using thin plantar inserts increased postural stability with a decrease in energy expenditure, as well as influenced ocular vergence.
  – Medial arch support caused an increase in the phasic amplitude of divergence.
  – Lateral arch support cause in increase in the tonic amplitude of convergence.
Hippocampal head-direction (HD) neurons may be continually monitoring vestibular inputs in order to construct a current estimate of spatial orientation.

Inactivation of the vestibular apparatus produces disorientation.

Disruption of head-direction cell activity following semicircular canal plugging has been observed, supporting the role for vestibular inputs in HD cell function.
Multisensory processing is defined as the influence of one sensory modality on activity generated by another modality.

Perhaps the most functionally and anatomically studied multisensory structure is not in the cortex, but the midbrain.

This six-layered region contains spatiotopic representations of visual, auditory and somatosensory modalities within its intermediate and deep layers.
Our most common, everyday activities and those that are most essential to our survival, typically involved moving within and throughout our environment.

Self-motion perception is typically experienced when an observer is physically moving through space including self-propelled movements such as walking, running, or swimming, and also when being passively moved while on a train or when actively driving a car or flying a plane.

Self-motion perception is important for estimating movement parameters such as speed, distance, and heading direction.

It is also important for the control of posture, the modulation of gait, and for predicting time to contact when approaching or avoiding obstacles.

It is also important for the formation of spatial memories when learning complex routes and environmental layouts.
Movement

During almost all natural forms of self-motion, there are several sensory systems that provide redundant information about the extent, speed, and direction of egocentric movement, the most important of which include dynamic visual information (optic flow), vestibular information, proprioceptive information from the muscles and joints, and the efference copy signals representing the commands of these movements.

Also important, although less well studied, are auditory signals related to self-motion and somatosensory cues provided through wind, vibrations, and changes in pressure.

Not only is it important to take a multisensory approach to self-motion perception in order to understand the basic science underlying cue combination, but it is also important to strive toward evaluating human behaviors as they occur under natural, cue-rich, ecologically valid conditions.
How do we perceive our direction of self-motion through space?

To navigate effectively through a complex three-dimensional (3D) environment, we must accurately estimate our own motion relative to objects around us.

Self-motion perception is a demanding problem in sensory integration, requiring the neural combination of visual signals (optic flow), vestibular signals regarding head motion, and perhaps also somatosensory and proprioceptive cues.

To understand the need for multisensory integration of these cues, it is useful to consider the strengths and weakness of each cue.
With regard to heading perception, the limitations of optic flow processing might be overcome by making use of inertial motion signals.

Limitations of the vestibular system is the inability to distinguish between translation and tilt relative to gravity.

This can be resolved using angular velocity signals from the semicircular canals, but the properties of the canals render this strategy ineffective during low-frequency motion or static tilts.

In the absence of visual cues, linear acceleration is often misperceived as tilt. Multisensory integration of visual and vestibular inputs provides dual benefits:

- It overcomes important limitations of each sensory system alone.
- It provides increased sensitivity when both symptoms are active.
There is little reason to believe that there would be a direct effect of gravity on the myosin molecule, but there are clear effects of gravity on the myosin molecule, presumably because of its effects on the whole organism and its neuromotor and endocrine systems.

For example, the direct mechanical effect of gravity on eye position is minimal.

– However, the neural control of eye position is highly sensitive to the removal of gravitational loads on the whole body.
The disruption of eye control after exposure to microgravity is not surprising, given that the neural control of the eyes evolved in a 1-G environment and the coordination of the eyes must be synchronized with the sensory and motor commands of the whole body.

The eyes cannot be controlled effectively independently of head and body position, and the neural control of the head and body position must be and is highly dependent on gravity.
Gravitational Biology of the Neuromotor Systems

Neural control of the distribution of blood in varying gravitational environments must be correlated with neural control of skeletal muscles.

A classic example of this coordination is the orthostatic response to standing from a supine position.

It is well documented that, even after short periods of microgravity or bed rest, a sudden rise to an upright position can result in an episode of orthostatic intolerance, i.e., Fainting.
Gravitational Biology of the Neuromotor Systems

The human genome evolved in a 1-G environment, which imposes a remarkably predictable amount of muscular work and includes a strategy to replace the amount and kind of substrates used in the cells that do the work.

We seem to have failed to recognize the importance that the 1-G environment has had in shaping the integrative functions of the genome.

Understanding the responses of the normal biological systems to microgravity may help considerably in developing strategies to overcome the plethora of biological disorders associated with extremely sedentary lifestyles.
Cerebellum

Static neck input modulates the responses of anterior vermis Purkinje cells during complex vestibular stimulation.

It is likely that Purkinje cells in the anterior vermis might also encode motion in a body-centered reference frame.

These neurons in the vermis and rostral Fastigial nuclei, which are tightly coupled to spinal function, may give rise to appropriate responses in the limb musculature by modifying the spatial organization of the vestibulospinal reflexes according to the requirements for body stability.

The two balance organs located in the left and right temporal bone, the vestibular nerves, the vestibular nuclei, the vestibulo-cerebellum, and the vestibular cortex are the major structures that together form the vestibular system.
To allow detection of body movement and orientation in space we use vision, proprioception (including gravitoreceptors along the large blood vessels), hearing, and the vestibular system.

The vestibular system makes use of specialized sensor systems located in the head to monitor the angular accelerations (rotations in three dimensions) and linear accelerations (translations in 3D and tilt relative to the gravity vector) of the head in space.

During head movements many forces act upon these sensors and often all sensors are stimulated simultaneously. On earth, head movements always occur within the gravitational field and are often composed of both rotations and translations.

The membranous labyrinth consists of a series of tubes and sacs enclosed in the similarly shaped channels of the bony labyrinth.

Making up the vestibular portion of the membranous labyrinth are the utricle, the saccule, and the three semicircular canals.

The vestibular hair cells are composed of a cell body and a bundle of cilia on top of them, on average about 50 stereocilia to 1 kinocilium.
Tilt vs Translation

• The visual and somatosensory system support the otolith organs for detection of constant linear acceleration and tilt perception at low frequencies, whereas the semicircular canals support the otolith organs in distinguishing true body tilt from translations at frequencies above 0.1 Hz.

• If different sensory systems give conflicting or insufficient information, hindering the determination of the direction of gravity or distinguishing correctly between environmental and self-motion, motion sickness is quite common, especially in those individuals with substantial active vestibular projections to the autonomic nervous system.
Translation vs Tilt

• Because of the physical limitations of the peripheral sensors, two important central integrators ensure proper evaluation of vestibular information.
  
  – 1. The velocity storage is a multisensory element whose function is to compute an accurate estimate of rotation velocity using multiple sensory cues (canals, otoliths, vision). An accurate estimate of rotation is critically important not only for itself but also for accurate estimation of tilt and translation.
  
  – 2. A tilt estimator uses canal and otolith information to compute a robust central estimate of tilt.
Velocity Storage

• The vestibular rotation pathway is dedicated to detecting fast rotations of the head. Its main feature is the velocity storage, which improves the signal of the canals.
  – Its main feature is the velocity storage (inverse dynamic model), which improves the signal of the canals.
    • The visual pathways allow the rotational retinal flow to influence the velocity storage and participate directly to the estimate of rotation.
    • The inertial pathways, where rotation information is integrated into an estimate of head tilt, disambiguate the otolithic signal.
Vestibular Reflexes

- The organization of vestibulocollic reflexes (VCRs) is more complicated than that of the AVOR.
- Many more muscles are involved (30 vs 6), these have more diverse pulling directions, and there can be rotations around several axes.
Canal-Otolith Convergence

- Many central vestibular neurons get convergent canal and otolith inputs.
- Most convergent cells receive excitatory inputs from at least two end organs, with one or both inputs being monosynaptic.
- In the cat, canal-otolith convergence is more prominent in neurons receiving vertical-canal, rather than horizontal-canal inputs.
Convergence from Somatosensory Receptors

- The predominant input to the vestibular nuclei is from the peripheral labyrinth, but neurons in these nuclei also receive inputs form other sources.
- One source is the somatosensory system as there are pathways from all levels of the spinal cord linking peripheral sensory receptors with the vestibular nuclei.

Vestibular Convergence

- Stimulation of neck muscle afferents can excite or inhibit VN neurons, usually at latencies of 10 to 15 ms.
  - These short latencies are consistent with the presence of disynaptic pathways, believed to begin with muscle spindle afferents from neck perivertebral muscles.
  - One route from neck afferents to the VN is via monosynaptic connections with the central cervical nucleus (CCN).
  - Spinocerebellar axons from the CCN send collaterals to the contralateral vestibular nucleus.
Input from Limb Afferents

- The central cervical nucleus receives input not only from neck afferents but also from the vertical semicircular canals.
- The activity of Deiters neurons is modified by movement or palpation of most parts of the body surface, as well as by stimulation of both forearm and hindlimb nerves.
- Signals evoked by such stimuli can reach the vestibular nuclei by a variety of pathways, some fairly direct, others complex.
Vestibular Convergence

- In the VN, limb inputs can produce a mixture of facilitation and inhibition.
- The latency of facilitation is long, 10 to 35 msec.
- There is no obvious pattern in the distribution of facilitation within the VN.
- It affects neurons that respond to natural vestibular stimulation with dynamics suggestive of inputs from semicircular canals and otolith organs.
- Stimulation of nerves from either fore- or hindlimb nerves facilitates vestibulospinal neurons projecting to the cervical or to the lumbar cord.
- Stimulation of somatic nerves can activate Purkinje-Cells, which in turn inhibit VN neurons.
Vestibular Convergence

- There is a tendency for vestibulospinal neurons projecting to the lower (hindlimb) segments of the spinal cord to be inhibited by stimulation of hindlimb nerves, while those projecting to cervical (forelimb) levels are inhibited by stimulation of forelimb nerves.
- The fact that stimulation of muscle and cutaneous nerves from the limbs evokes a widespread facilitation, modulated by a patterned inhibition, in areas of the VN projecting to the spinal cord as well as in areas projecting to the extraocular motor nuclei suggests that somatosensory inputs have specific functions.
Vestibular Convergence

- More than half of the VN neurons that receive input from the labyrinth also receive input from the neck.
- Neck and vestibular inputs add linearly, acting synergistically in some neurons but antagonistically in many more.
- When antagonistic inputs have comparable gain and phase, rotation of the head, activating receptors in both the labyrinth and the neck, results in cancellation.
- For many neurons, when the head was rotated on the body, activating both neck and vestibular receptors, there was partial or even total cancellation of the response.
Vestibulo-Autonomic Connections

- Postural changes necessarily alter the gravitational forces acting on the cardiovascular and respiratory systems.
  - While there are non-vestibular mechanism (eg. Baroreceptor reflexes) involved in these compensatory responses, the vestibular system makes a contribution.
The existence of a functional interaction between the vestibular system and the autonomic nervous system was hypothesized in the 1920's based on clinical observations and is now supported by a plethora of research.

The peripheral vestibular system is thought to be involved in both a short and long latency, feedforward mechanism to stabilize the effects of postural adjustments on blood pressure, while the arterial baroreceptors contribute in a feedback regulatory mechanism that regulates sympathetic tone.

The vestibular system most likely interacts with the autonomic system through the vestibulo-sympathetic reflex pathway which is estimated to be 3-10X faster than the baroreflex for effecting changes in blood pressure.
Humans demonstrate a number of unique adaptations that allow for the maintenance of blood pressure and brain blood flow when upright.

Anatomical evidence in animals demonstrates that neural connections are present between the vestibular nuclei and cerebral vessels through two possible pathways. Connections have been found between the Vestibular Nuclei and the Fastigial Nucleus, then to the Rostral Ventrolateral Medulla, followed by vasodilatory connections to the cerebral vessels.

• Similarly, neurons travel from the Vestibular Nuclei to the Nucleus Tractus Solitarius and then to the Pterygopalatine Ganglion, resulting in cerebral vasodilation.

• The experimental results support our hypothesis and provide evidence that activation of the vestibular apparatus, specifically the otolith organs, directly affects cerebral blood flow regulation, independent of blood pressure and end tidal CO₂ changes.
Applications

- Manual Therapy - spinal manipulation, complex movements, myofascial techniques.
- Vestibular Rehabilitation and Mental Imagery
- Core stability
- Primitive Reflex Exercises and visual gaze stabilization
- Dietary Modifications
- SSEP and ARPWAVE electrical stimulation
- Endless therapies with knowledge of the human nervous system
Questions?
there is hope
I was referred to Dr. Schmoe by a fellow pro athlete who had sought his care after a couple concussions. I had no preconceived ideas about what to expect, but at this point I was trying to stay open minded and take a proactive approach to my recovery.

After about a week of therapy and testing I began to see changes. The most notable being an **INCREASE IN COORDINATION** and **OVERALL BODY AWARENESS**. Movements that had just felt "off" for a long time seemed to have been corrected.

I felt like a better athlete.

My running gait had noticeably improved and even my walk was a bit different. I kept in touch with Dr. Schmoe and his team well after my visit and felt that there was a genuine interest in my health and well being. It was well worth the trip.

**Dane Sanzenbacher**

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What should you look for in concussion rehabilitation support?
Reading Material

**Vestibular Anatomy and Physiology**
- The Vestibular System: A sixth sense. Goldberg, Wilson, Cullen
- The Neural Bases of Multisensory Processes. Murray, Wallace

**Vestibular Pathology and Diagnosis**
- Clinical Neurophysiology of the Vestibular System. Baloh, Honrubia
- Vertigo: Its multisensory syndromes. Brandt

**Vestibular Testing and Diagnosis**
- Oxford Textbook of Vertigo and Imbalance. Bronstein
- The Neurology of Eye Movements. Leigh, Zee Module 943: Neurological Examination and Diagnosis
- Neuroanatomy through Clinical Cases. Blumenfeld
- Neurological Differential Diagnosis. Patten
- Neurologic Examination. DeJong
- The Neurologic Examination. DeMyer

**Vestibular Rehabilitation**
- The Clinical Science of Neurological Rehabilitation. Dobkin
- Vestibular Rehabilitation. Herdman