NeuroRehabilitation 50 (2022) 279–296
DOI:10.3233/NRE-228012
IOS Press

Review Article

Vestibulo-ocular dysfunction in mTBI: Utility of the VOMS for evaluation and management – A review

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Abstract.
BACKGROUND: Individuals who have suffered a concussion/mild traumatic brain injury (mTBI) frequently report symptoms associated with vestibular and/or oculomotor dysfunction (VOD) like dizziness, nausea, fatigue, brain fog, headache, gait and neurocognitive impairments which are associated with the development of chronic symptoms. The Vestibular/Ocular Motor Screening (VOMS) tool has been established as a reliable and clinically relevant complement to use alongside a battery of post-concussion tests to improve screening and referral for further evaluation and treatment of VOD.
OBJECTIVES: This paper will review the pathoanatomy and symptomatology of common vestibular and oculomotor disorders after concussion, as well as the utility of the VOMS to assist in diagnosis, referral, and management.
METHODS: Primary articles were identified using a search via PubMed, Google Scholar, OneSearch, and CINAHL. Search key terms were combinations of "mild traumatic brain injury" or "concussion" or "pursuit" or "accommodation" or "vergence" or "convergence insufficiency" or "saccades" or "vestibulo-ocular reflex" or "vestibular ocular motor screen" or "vestibular rehabilitation", or "vision rehabilitation" including adult and pediatric populations that were published in print or electronically from 1989 to 2021 in English. Classic papers on anatomy of eye movements, vestibular system and pathological changes in mTBI were also included, regardless of publication date.
RESULTS: Objective impairments are commonly found during testing of smooth pursuit, saccades, vergence, accommodation, vestibular ocular reflex, and visual motion sensitivity after mTBI. These deficits can be actively treated with vestibular physical therapy and oculomotor/neuro-optometric vision therapy. VOMS is an efficient and reliable tool that can be used by all healthcare and rehabilitation providers to aid in diagnosis of post-concussion VOD, to help facilitate the decision to refer for further evaluation and treatment to expedite symptomatic post-concussion recovery.
CONCLUSIONS: VOD is common after concussion in acute, post-acute, and chronic phases. Once areas of impairments are identified through proper assessment, clinicians can maximize recovery by referring to vestibular physical therapy and/or neuro-optometry to design a targeted treatment program to address individual deficits.

Keywords: Concussion, post-concussion syndrome, mTBI, VOMS, vestibulo-ocular dysfunction, oculomotor dysfunction, vestibular rehabilitation, vision rehabilitation, vision therapy

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1. Introduction

Globally, an estimated 64 to 74 million new cases of traumatic brain injury (TBI) occur each year (Dewan et al., 2018). The vast majority (70–90%) of these are classified as mild traumatic brain injury (mTBI), also referred to as concussion. Due to the acute and possible long-term impact of symptoms associated with mTBI, the US Centers for Disease Control and Prevention (CDC) has deemed concussion a significant public health concern (Lumba-Brown et al., 2018). While many studies report most individuals recover within a relatively short period of time, approximately 1 week to 1 month post injury (Collins et al., 2016; McCrea et al., 2003; Iverson et al., 2017), others suggest that up to 58% of patients may develop persistent symptoms lasting longer than 1 month (Bazarian et al., 1999; Iverson, 2005), sometimes clinically referred to as post-concussion syndrome (PCS).

Numerous studies indicate impairments in the vestibular and oculomotor systems are particularly common after concussion. The appearance of vestibular-oculomotor dysfunction (VOD) in concussion is a significant risk factor for development of chronic post-concussion symptoms, as subjects with evidence of VOD at initial clinical consultation in acute concussion have a 4x increased risk of developing PCS (Ellis et al., 2015; Master et al., 2018). Eye movement abnormalities can be an objective biomarker for assessing concussion, as eye movement control relates to neurological functional integrity (Heitger et al., 2009). Over the past few years, numerous government and medical organizations have released consensus recommendations that include performing vestibulo-oculomotor testing when diagnosing concussion (Halstead et al., 2018; Lumba-Brown et al., 2018; Marshall et al., 2015; McCrory et al., 2017).

Accurate diagnosis of vestibular and oculomotor impairment in concussion with appropriate referral for vestibular physical therapy and/or oculomotor vision therapy can expedite the recovery of concussion (Alsalaheen et al., 2010; Collins et al., 2016). The development of the Vestibular/Ocular Motor Screening (VOMS) assessment tool has provided a validated and easy way to screen patients with potential concussion and can be used by numerous providers across disciplines (Mucha et al., 2014). This paper reviews the clinically relevant pathophysiology and symptomatology of common vestibular and oculomotor disorders encountered post-concussion, as well as the utility of VOMS as a multi-disciplinary screening assessment tool to aid in clinical diagnosis and management.

2. Epidemiology of vestibular-oculomotor dysfunction after concussion

Studies on the epidemiology of VOD vary due to differences in age, time since injury, mechanism of concussion, methodology, and types of VOD evaluated. In the pediatric population with mTBI, VOD is prevalent in up to 76% with acute concussion and 24% with PCS (Ellis et al., 2015). In the adult population with mTBI, estimates of those exhibiting signs and symptoms of VOD vary between 50–90% (Alvarez et al., 2012: Capó-Aponte et al., 2012; Ciuffreda et al., 2007; Goodrich et al., 2007; Suh et al., 2006a).

Range of prevalence for the most common vestibular and oculomotor impairments post-concussion include smooth pursuit dysfunction (43–60%), saccadic dysfunction (21.6–30%), convergence insufficiency (47–55%), accommodative dysfunction (35–54.2%) (Capó-Aponte et al., 2012; Gallaway et al., 2017; Master et al., 2016; Merezhinskaya et al 2019; Suh et al., 2006b), vestibular-ocular reflex (VOR) impairment (0–71%) (Bogle, 2019), visual motion sensitivity, and balance deficits (40–68%) (Alsalaheen et al., 2010; Mucha et al., 2014). The oculomotor and vestibular systems overlap in symptomatology and pathoanatomy, and it is important to understand each system's independent contributions post-concussion to effectively manage and rehabilitate.

3. Pathoanatomy and symptomatology of specific vestibular and oculomotor deficits after concusssion

3.1. Vestibular system

Among other etiologies, vestibular symptoms post-concussion may be related to peripheral (Brodsky et al., 2018b) and/or central vestibulopathy (Alihiali et al., 2014). The vestibular system is a complex network that includes the peripheral components, including small sensory organs of the inner ear (utricle, saccule, and 3 semicircular canals), and central connections to the brain stem, cerebellum, cerebral cortex, visual system, and postural muscles.

The peripheral apparatus is organized into two distinct functional units: the vestibulo-ocular system, which maintains visual stability during head and body movements, and the vestibulo-spinal system, which is responsible for postural control (Cullen, 2012). These two functional vestibular networks do not share identical neuronal circuitry, therefore it is possible to have impairments of the vestibulo-ocular system without impairments of the vestibulo-spinal system and vice versa, or both (Allum, 2012). Impairments in the vestibulo-ocular system commonly manifest as symptoms of dizziness and visual instability. Conversely, vestibulo-spinal system dysfunction commonly results in disrupted balance (Khan & Chang, 2013). The vestibulo-spinal system includes the otoliths (the utricle and saccule), which are sensitive to gravitational and linear acceleration (Cullen, 2012).

The semicircular canals are sensitive to rotational acceleration in all directions of space and each has a particular orientation with neural connections to a specific pair of extraocular muscles (EOMs) that lie roughly in the same plane. Once a canal is stimulated, the afferent information is relayed via cranial nerve VIII to the brainstem and vestibular nuclei (Cohen, 2013), and the associated EOMs are either stimulated or inhibited, thereby driving the direction of ocular motion in order to maintain visual stability while the head/body is in motion. The cerebellum plays an adaptive role to modify and recalibrate information from the vestibular system (Hain & Helminski, 2007). Information is also sent to the parietal and temporal lobes for further processing and integration (Cohen, 2013).

3.2. *Vestibular-Ocular Reflex*

The orientation of the semicircular canals and the EOMs that parallels its action is the basis of the vestibulo-ocular reflex (VOR) (Cohen, 2013). When the head or body is in motion, the brain constantly monitors visual clarity. If visual clarity is not maintained, the brain will employ a corrective eye movement to hold the eye position in space while the head/body moves, so that the image on the retina of the eye is stable and clear. This is called the VOR and it enables individuals to constantly maintain stable vision while the head and/or body is in motion. There are two types of VOR: the angular VOR which stabilizes vision during rotational head movements using the semicircular canals, and the translational VOR which stabilizes vision during linear acceleration of the head and body using the utricle and saccule. The VOR acts independently of saccades, pursuits, vergence, and accommodation, which are visually mediated eye movements (Leigh & Zee, 2015). Vestibular signals that are produced as a consequence of reflex head movements are suppressed allowing for appropriate saccade or pursuit eye movements. Therefore, mismatch of visual information with other sensory motor feedback system elements can cause one to perceive an image as moving or shifting when it is not (Cohen, 2013). There is limited research into the prevalence of VOR specific dysfunction post-concussion. Some studies demonstrate a wide range of objective abnormalities in the VOR pathways from 0–71% (Bogle, 2019) and symptomatic reproduction with VOR testing range in up to 61% (Mucha et al., 2014).

Symptoms of VOR dysfunction include but are not limited to nausea, imbalance, dizziness, movement-related blurry vision, unsteadiness, vertigo, anxiety in busy environments and visual motion sensitivity (Akin et al., 2017, Mucha et al., 2014). Children/adolescents (8–18 years old) and adults who experience dizziness/vertigo report considerably lower physical and emotional well-being (Deissler et al., 2017; Ten Voorde et al 2012; Weidt et al., 2014).Vestibular symptoms post-concussion may be related to peripheral vestibulopathy (Brodsky 2018b), central vestibulopathy due to injury to the cerebellum, thalamus, hippocampus, and oculomotor pathways (Alhilali et al., 2014), posttraumatic headache or migraine (Heyer et al., 2016, Stolte et al., 2015), autonomic dysfunction, altered multisensory integration (Bogle, 2019) and/or possible psychiatric concerns (Fife & Kalra, 2015).

While central vestibular dysfunction is common, peripheral vestibular dysfunction can also occur in head injury. Benign paraoxysmal positional vertigo (BPPV) occurs when one or more of the calcium carbonate crystals in the utricle become dislodged and migrate into a semi-circular canal. BPPV is often described as true vertigo, or an illusory sensation of motion of either the self or the surroundings in the absence of true motion and is produced by changes in the position of the head in relationship to gravity, lasting for a short duration of time (Bhattacharyya et al., 2017). Post-concussion, adults demonstrate BPPV in 5–57% of cases, while children and adolescents present less frequently in 5–20% of cases. Children with migraine diagnoses are five times more likely to present with BPPV (Bogle, 2019; Liu 2012).

3.3. The visual and oculomotor system

The visual system is particularly vulnerable to the effects of brain injury due to its expansive anatomy and physiology throughout the brain (Singman, 2013), as approximately 70% of the brain is used for visual and sensory processing (Suter, 2010). This large vision neuro-network requires efficient afferent and efferent neural interconnections and processing from multiple areas of the brain including frontal, parietal, temporal, and occipital cerebral cortices, brainstem, midbrain, cerebellum, cranial nerves, and axonal interconnections (Kelts, 2010; Leigh & Zee, 2015).

The peripheral oculomotor system consists of the six extraocular muscles of each eye (superior rectus, inferior rectus, medial rectus, lateral rectus, superior oblique, and inferior oblique) and their corresponding efferent cranial nerves (III, IV, and VI) as well as autonomic innervation of the pupil and accommodative systems. Eye movements are controlled and coordinated centrally via a variety of corticonuclear and tectobulbar tracts that connect fibers from the cerebral hemispheres and superior colliculi to the cranial nerve III, IV, and VI nuclei in the midbrain. From the midbrain, tracts extend along the medial longitudinal fasciculus into the spinal cord, connecting the oculomotor and vestibular systems.

The initiation of an eye movement horizontally, is a different neural pathway than that required to initiate an eye movement vertically, as is the coordination of both eyes moving from one distance to another. The complexities of the neural circuits required to coordinate efficient and asymptomatic eye movements in a three-dimensional visual environment are extensive and are still not fully understood pathophysiologically (Leigh & Zee, 2015). Every eye movement described below has a different neural pathway with connections to other sensory systems to allow the brain to constantly monitor its own oculomotor performance and adjust according to changes in head/body position as well changes in the visual environment. It is this unique aspect of the pathoanatomy of the visual system that allows patients post-concussion to have symptoms with one or more eye movements, in one or multiple directions, and symptoms that may not be considered to be classically linked to a visual etiology.

Post-concussion vision symptoms include blurred vision, double vision, ocular strain, ocular fatigue, light sensitivity, difficulty taking notes in class, reading difficulties, impaired visual-based concentration, and frontal headaches associated with visual activity (Mucha & Trbovich, 2019). In patients who have sustained a concussion, abnormal oculomotor function has been strongly associated with cognitive and gait impairments, (Howell et al., 2018b; Pearce et al., 2015) worse neurocognitive performance (Galetta et al., 2011; Galetta et al., 2013; Tjarks et al., 2013), as well as protracted recovery (DuPrey et al., 2017; Ellis et al., 2015). Additionally, there are many non-visual physical, mental and emotional symptoms like headache, fatigue, inattention, mental fogginess, disorientation, nervousness, and anxiety that may occur secondary to post-concussion oculomotor dysfunction but go misdiagnosed/untreated (Laukkanen et al., 2016)

3.4. Smooth pursuits

Smooth pursuit eye movements are a type of conjugate eye movement that primarily allows both eyes to simultaneously follow a slow-moving target and maintain that image on the retina as the target moves. Smooth pursuits also work with the VOR to help maintain fixation on a target when the head and body is in motion (Leigh & Zee, 2015). When smooth pursuits are impaired, the eyes will lose track of the moving object and use a saccadic eye-movement to recover or “catch up” to the target, making abnormal smooth pursuits look jerky on clinical examination.

The neural pathway underlying smooth pursuits is not yet fully understood but includes striate, extrastriate, and brainstem structures. Horizontal pursuits involve areas of the middle temporal, medial superior temporal areas of the visual cortex, as well as the frontal and supplemental eye fields (FEF/SEF) and posterior parietal cortex. Visual information from the FEF projects to the dorsolateral pontine nuclei, which sends projections to the cerebellum. Cerebellar structures then project to the medial vestibular nucleus in the brainstem. Unlike horizontal smooth pursuits, vertical smooth pursuits include the rostral nucleus reticularis tegmenti pontis instead of the dorsolateral pontine nuclei and the y-group nucleus instead of the medial vestibular nucleus (Wong, 2008; Hunfalvay et al., 2020). The frontal areas involved in both smooth pursuits and attention are connected to the cerebellum which represent the longest white matter tracts of the brain that are extremely vulnerable to damage from TBI (Contreras et al., 2011).

Smooth pursuit impairments range from 43–60% of individuals with mTBI (Hunt et al., 2016). Objective findings include target errors (saccadic intrusions) and variability in speed of pursuit (Suh et al., 2006a; Suh et al., 2006b). Subjectively, patients with pursuit dysfunction report visual motion sensitivity, dizziness, and nausea when following moving targets like traffic or action movies on the television, or difficulty with scrolling on screens.

3.5. Saccades

Saccadic eye movements are a conjugate eye movement that allow both eyes to move quickly in the same direction, rapidly shifting the eyes from one object of visual interest to another. Saccades can be made voluntarily or reflexively to visual, auditory, memory, and tactile stimuli. Clinically, when saccades are inaccurate in mTBI, they have been characterized as hypometric (undershoot the target) or hypermetric (overshoot the target), have slower velocities/increased latency, and smaller peak accelerations (Heitger et al., 2006; Heitger et al., 2009; Kraus et al., 2007).

Saccades are initiated by signals processed from the retina, cerebral cortex, superior colliculus, basal ganglia, thalamus and cerebellum (Leigh & Zee, 2010). The motor movements are generated from burst neuron signals in the brainstem but controlled by the cerebral cortex. Vertical and torsional saccades originate from the premotor area at the rostral mesencephalon in the midbrain, whereas horizontal saccades are generated from the paramedian pontine reticular formation in the pons (Wong, 2008). Evidence suggests a joint/shared premotor pathway in the brainstem for the saccades and smooth pursuits (Keller & Missal, 2003).

With multiple premotor areas and motor cortical pathways, control of smooth pursuits and saccades appears to be prone to diffuse axonal injury (Ciuffreda et al., 2007). Saccadic dysfunction occurs in 21.6–30% of patients with mTBI (Capó-Aponte et al., 2012; Ciuffreda et al., 2007; Master et al., 2016; Merezhinskaya et al., 2019). Symptoms of patients with saccadic dysfunction may include dizziness with eye movements, headaches when reading, eyestrain, losing their place when reading, re-reading, difficulty with eye contact, difficulty reading on screens, and symptom provocation when watching fast moving objects or shifting gazes laterally or vertically.

3.6. Vergences

Vergence eye movements are a disconjugate eye movement used to track an object moving closer or further away as well as look at objects that are located at different distances away. When looking at objects further away, both eyes move outwards, termed divergence. When looking at objects approaching closer, both eyes move inwards towards the nose, termed convergence. Both eyes need to make these movements at the same speed and magnitude in order for the brain to interpret a single and fused image perception (binocular vision). If the eyes do not move together in sync, the brain will either perceive two distinct images (ie double vision) due to the mismatched input from each eye, or the brain will perceive an overlap of images, which may be perceived as blurry vision or shadowing.

There are multiple types of vergence eye movements including tonic, proximal, fusional, and accommodative vergence that are employed depending upon eye alignment, object distance, and image blur. In addition to horizontal vergence movements like divergence and convergence, the eyes also adjust vertically and torsionally using vertical and cyclovergence, which is necessary to stably view a three-dimensional, dynamic visual environment. Each type of vergence has a different expansive neural pathway throughout the brain that is not yet fully mapped but includes cerebral, cerebellar, and brainstem areas (Leigh & Zee, 2015; Wong, 2008)

Each aforementioned type of vergence requires different types of optometric testing to fully measure function in both amplitude (strength) and flexibility (speed) (Scheiman & Wick, 1994). Near point of convergence (NPC) is the measurement of the amplitude of proximal convergence, or how much a person is able to cross their eyes inward while following an approaching near target. Normative studies have shown that a person should be able to converge up to 5 cm (Convergence Insufficiency Treatment Trial (CITT) Study Group, 2008) from the bridge of their nose before seeing double (subjective endpoint) or when the clinician performing the test sees an eye deviate away from the target (objective endpoint) (Maples & Hoenes, 2007). Once diplopic, it is normal for the eyes to recover or regain single vision of that target as it moves outward within 2cm of the break point and/or 7cm from the bridge of the nose (Scheiman et al., 2003). NPC is a critical screening measurement in brain injury, as a decreased NPC has been reported in 30–56% of patients post-TBI and has been reported as a prevalent deficit found in patients with a history of TBI (Pearce et al., 2015; Howell et al., 2018a). This prevalence is substantially higher than that found in 5% of the general non-TBI population (Scheiman et al., 2003).

Reduced convergence can contribute to difficulties with reading including but not limited to losing one's place while reading, double vision, eyestrain, and fatigue (Convergence Insufficiency Treatment Trial (CITT) Study Group, 2008). Additionally, reduced NPC has also been linked to neurocognitive impairment on IMPACT testing and symptom assessments. Notably, post-concussive patients with reduced NPC perform worse on the verbal memory, visual motor speed, and reaction time components of IMPACT testing (Pearce et al., 2015). Reduced NPC has also been associated with gross motor system dysfunction including slower gait speed, shorter stride lengths, and dual-task average walking speed compared to controls with concussion that did not have a reduced NPC (Howell et al., 2018c). Moreover, a reduced NPC is identified with prolonged concussion recovery (DuPrey et al., 2017).

3.7. Accommodation

Accommodation is the ability for each eye, individually, to engage the ciliary body muscle behind the iris, to flex the intraocular lens and produce a clear image onto the back part of the eye, called the retina. The amount of accommodation or visual clarity or "focus" is dependent upon how close an object is relative to the eye, as the eye needs to increase accommodation the closer the object is. Accommodative ability declines with age and is dependent upon the accuracy of an individual's corrected refractive error in glasses or contacts. The accommodative neurological pathway is extensive and intertwined with the parasympathetic pupillary light reflex pathway. Blur signals travel along the afferent visual pathway to the primary visual cortex in the occipital lobe, sending projections that eventually integrate information from both cerebral hemispheres as well as higher-order visual processing information from the parietal and temporal lobes. Neural projections are sent to the Edinger-Westphal nucleus via various pathways from the superior colliculus, pons, and cerebellum, ultimately leading to a parasympathetic innervation of the ciliary ganglion, and subsequent innervation of the ciliary muscle via the short ciliary nerves (Richter et al., 2000). If the eye is unable to accommodate on a target at a certain distance appropriately, the person will experience symptoms such as blur, eye strain, headaches, changes in focus, nausea, and dizziness.

Near point of accommodation (NPA) is the measurement of the amplitude of accommodation, or how much a person is able to engage their focus as an object approaches their eye and still perceive the object to be clear. NPA is performed monocularly, with each eye separately. Accommodative insufficiency (AI) occurs when NPA is lower than expected norms for the patient's age. AI may also be caused and/or influenced by refractive errors including hyperopia, latent hyperopia, presbyopia, optical over-correction, neurologic and systemic disease and pharmacologic side-effects on the pupillary response and ciliary body (Yanoff et al., 2009). Accommodative spasm (AS) occurs when the accommodative system over-accommodates for a stimulus or the eye is unable to release focus after looking at a near target for a prolonged period of time. Additionally, the accommodative response can be latent and/or slow in speed, known clinically as accommodative infacility (Scheiman & Wick, 1994).

Accommodative disorders are one of the most frequent oculomotor problems in concussion occurring in ~51% of post-concussion adolescents (Master et al., 2016) and frequently ~78% occur concomitantly with post-concussion convergence insufficiency (CI) disorders (Raghuram et al. 2019). Accommodative disorders can cause symptoms similar to those of convergence disorders and are also common developmentally in adolescents without concussion (Scheiman et al., 2011). Developmental accommodative disorders are present in approximately 17% of the general population, however, prevalence rates vary significantly based on the study and geographic location from <1% up to 61.7% (Cacho-Martinez et al., 2010). Alvarez and colleagues (2021) found persistent post-concussion symptomatic CI patients to have a significantly worse mean NPA than patients with developmental CI. The rate of comorbidity has been linked to the severity of the CI (Marran et al., 2006). Further, accommodative disorders have been found in up to 41% of TBI patients with reduced NPC (Raghuram et al., 2019).

In an attempt to increase convergence and relieve diplopia or blur at near, some patients may over-accommodate, which can lead to an AS (Faucher & De Guise, 2004). Patients with AS often complain of headaches with prolonged near work and blurry vision at *distance* after they have been looking at near for a prolonged period of time (Satgunam, 2018). Though less common than AI, AS has been reported in patients following TBI (Chan & Trobe, 2002).

Changing viewing distance from far away to near with both eyes requires a combination of convergence, pupillary constriction, and accommodation in a coupled neural control system called the near reflex or triad (Myers & Stark, 1990; Faucher & De Guise, 2004). The near triad increases the depth of focus and maintains single, clear, binocular vision. (Von Noorden & Campos, 2002) AS can occur without abnormalities in the other two components of the near reflex (Sloane & Kraut, 1973). In some patients, the inability to accommodate causes a reduced ability to converge, due to the accommodative-convergence coupling, and thus causing a reduced near point of convergence, termed "pseudo-CI" (Von Noorden et al., 2004; Mazow et al., 1989; Wajuihian & Hansraj, 2016). These cases are more challenging as their convergence ability may not completely resolve with convergence exercises due to the underlying accommodative dysfunction. Patients with accommodation and convergence issues may have persistent symptoms beyond a year after head injury without appropriate neuro-optometric intervention (Merezhinskaya et al., 2019).

3.8. Fixation

The ability to voluntarily maintain eye alignment on any given target is an active and complex neurological process termed fixation which requires the activation of multiple eye movements including micro-saccades, accommodation, and vergences. Additionally, fixation depends upon the alignment of the two eyes relative to each other. Preexisting vertical and horizontal ocular misalignments occur in the general population $\sim$5% and are typically well compensated for by the patient's vergence system and/or optical lenses called prisms which correct the misalignment. The impact of mTBI on the oculomotor pathways can cause a patient to decompensate and manifest as an eye turn. Vertical and horizontal misalignment was found in 55% and 45% respectively in persons post-blast exposure (Capo-Aponte et al., 2017). Decompensated ocular misalignment can affect binocular vision tasks (pursuits, saccades, vergence) and influence gaze stability, resulting in diplopia (double vision), blurred vision, headache, eye strain, dizziness, difficulty reading, and can greatly affect recovery from concussion (Capo-Aponte et al., 2017; Master et al., 2016).

3.9. Visual motion sensitivity

The brain requires accurate and stable smooth pursuits and vestibular input to process visual motion and motion parallax (Nadler et al., 2009). A TBI can alter the multisensory integration of visual and vestibular information. As a result, individuals may become overly reliant on the visual system, resulting in a heightened awareness of visual motion, particularly when in visually complex environments (Guerraz et al., 2001). Younger patients may be at increased risk for motion sensitivity, as they are still developing appropriate multisensory integration of these symptoms (Bronstein, 2016; Steindl et al., 2006). Athletes with pre-injury history of motion sensitivity may demonstrate prolonged recovery (Sufrinko et al., 2017).

Due to the complexity of the ever-changing dynamic visual world and constant eye, head, and body movement of the individual, isolated vestibular and oculomotor movements are rarely employed independently in daily visual activities. Thus, some visual and vestibular symptoms may occur due to one or multiple dysfunctions of the vestibular-oculomotor systems.

4. Screening and diagnosis of vestibular and oculomotor deficits after concussion

Screening and examination of vestibular and oculomotor systems are part of the multidisciplinary assessment in concussion (Collins et al., 2016). Symptoms associated with these systems appear to be an important early marker for concussion, and prolonged recovery has been linked to the presence of dizziness and VOD in acute concussion (Corwin et al., 2014; Lau et al., 2011; Savola & Hillbom, 2003). While imbalance complaints are common within the first few days after concussion, the utility of balance assessments alone as a measure of a vestibular system injury is limited because objective clinical balance impairments recover quickly within 3–5 days after injury (Goodrich et al., 2007; Riemann & Guskiewicz, 2000). Therefore, additional clinical vestibular assessments are warranted that go beyond vestibulo-spinal measures to include vestibular and oculomotor aspects (Mucha et al., 2014).

The Vestibular/Ocular Motor Screening tool (VOMS) is a user friendly and clinically relevant tool that requires minimal equipment, takes 5–7 minutes to administer, and was created to standardize screening for vestibular and oculomotor problems related to concussion. Since its initial publication, it has been thoroughly studied, and clinically implemented in many athletic and military concussion assessments (Management of Concussion-mild Traumatic Brain Injury Working Group, 2016; Kontos 2021). Clinicians record baseline symptoms of headache, dizziness, nausea, and fogginess on a scale of 0 to 10 scale (0: none, 10: severe), and then re-assess symptoms following each of the six VOMS assessments: smooth pursuit, saccades (horizontal and vertical), near point of convergence (NPC), horizontal VOR, vertical VOR, and visual motion sensitivity (Mucha et al., 2014). Specific procedures can be found in the original publication (Mucha et al., 2014).

Positive findings or symptom provocation with any test may indicate vestibular and/or oculomotor dysfunction and should trigger a referral to the appropriate health care professional for more detailed assessment and management. The tool is complementary to and not a substitute for post-concussion balance assessments, neurocognitive testing, and symptom inventory. Neurocognitive testing (ImPACT) composite scores and VOMS item scores were largely unrelated in univariate comparisons, suggesting that the VOMS items capture aspects of concussive injury that are unique from ImPACT (Babicz et al., 2020).

Compared to controls, post-concussion subjects have much higher symptom reporting provoked during VOMS testing. In the original study, athletes without concussion never reported > 2/10 symptoms on any VOMS item. All VOMS items were positively correlated to the Post Concussion Symptom Scale (PCSS) total symptom score. Any individual VOMS item with a total symptom score of ≥ 2 increased the probability of being concussed by at least 46%. In addition, VOMS symptom scores over 2 and NPC distance greater than 5cm represented clinically useful cut-offs (50% and 38%, respectively) for identifying concussions. Three VOMS items (VOR, VMS, NPC distance) resulted in 89% accuracy for identifying patients with concussion from controls (Mucha et al., 2014).

VOMS screening has been studied in numerous settings since its conception in 2014. VOMS possesses excellent internal consistency ($\alpha = 0.92$) (Kontos et al., 2016; Moran et al., 2018) at initial and 6 month follow up (Kontos 2021), has high test-retest reliability (Anderson et al., 2015; Worts et al., 2018;Yorke et al., 2017), and low false-positive rates (between 2% and 11%) (Kontos et al., 2016; Yorke et al., 2017). Further studies support that VOMS testing can help differentiate those with concussion from healthy controls (Mucha et al., 2014; Yorke et al., 2017), is not affected by physical exertion (Worts et al., 2018), and demonstrated discriminant validity when compared to other concussion measures (Yorke et al., 2017).

Consistent with other studies evaluating post-concussion VOD, Anzalone (2017) found the VOMS assisted in predicting recovery time following sport-related concussion, and abnormalities on the VOMS in any domain (except for NPC and accommodation) may be associated with delayed recovery after sport-related concussion in youth and adolescents (Anzalone et al., 2017).

All VOMS items were also independently associated with concussion symptom severity and were significantly associated with concussion symptom severity scores independent of sex, baseline vestibular and ocular motor symptom ratings, and neurocognitive performance. Looking at the individual components of VOMS, saccades contributed more to concussion symptom severity than VMS and may be more likely to impact the individual. Symptom provocation during saccadic eye movements may be an independent predictor of concussion symptom severity (Babicz et al., 2020).

All VOMS items were strongly correlated with one another (Babicz et al., 2020; Moran et al., 2018), even on baseline assessment, and there is preliminary support for the implementation of VOMS baseline assessment into clinical practice (Moran et al., 2018). Baseline VOMS testing in healthy, non-concussed collegiate athletes, revealed that among subjects with VOMS scores above the clinical cutoff levels, 72% had a history of motion sickness, and were more often female than male. Other studies have also found that women tend to have higher VOMS scores than men (Sufrinko et al., 2017). Interestingly, previous history of concussion and migraines, known risk factors for concussion-related outcomes, were not associated with VOMS scores above clinical cutoff levels at baseline (Kontos et al., 2016).

VOMS results may help in understanding if the patient has likely sustained a concussion, point the provider towards the impaired areas, and assist in designing a treatment program to address deficits. While there are many strong reasons to utilize the VOMS, the screener has many limitations. In the original study, data was collected exclusively among healthy athletes 9–40 years old, by sports medicine providers, limiting exam generalizability (Mucha et al., 2014). Some studies on VOMS with subject demographics more reflective of the general population suggest that non-athletes may be more symptom-provoked due to less developed oculomotor and balance systems (Corwin et al., 2018), therefore specific score cutoffs from the original study may not be applicable to the general non-athlete population.

Additionally, a proportion of non-concussed children may demonstrate failures on a single exam element, specifically on the tests of horizontal and vertical saccades (Corwin et al., 2018), and/or on NPC as developmental CI is prevalent in 2–33% of the general population and can occur in other neurological conditions (Cacho-Martinez et al., 2010; Scheiman et al., 2003). Thus, one or two failed VOMS elements, in the absence of other symptoms, may not be sufficient for a concussion diagnosis (Corwin et al., 2018).

Without a baseline or pre-injury measurement of NPC, it is unknown if an abnormal NPC post-concussion is pre-existing, exacerbated, or fully caused by the concussion itself. When possible, authors suggest baseline/pre-injury measurement of NPC to provide more confidence in the diagnostic utility of NPC assessment after a suspected concussion (Yorke et al., 2017). In addition, during VOMS, NPC is repeated three times, as a person may have a normal NPC on the first trial, but the system may fatigue with repeat attempts (Ernst et al., 2020; Scheiman & Wick, 1994). While the VOMS protocol only records the subjective/objective endpoint of NPC (double vision break), it is an optometric standard of care to also record the recovery of NPC, as many patients with convergence issues may have normal amplitude break but reduced recovery.

VOMS was designed as a subjective screening tool for self-reported symptoms and has not been validated against standardized measures of vestibular and ocular-motor function. VOMS was not designed as a comprehensive tool for vestibular and oculomotor function and does not encompass all diagnostic strategies necessary to examine all aspects of vestibular and oculomotor dysfunction, like accommodative and vergence function. Furthermore, improvements in self-reported symptom provocation cannot be extrapolated to objective improvements on standardized measures of vestibular and ocular-motor function (Alsalheen et al., 2020). Therefore, VOMS is not a stand-alone tool, nor a treatment paradigm and should be included in the post-concussion test battery as a screening tool to point clinicians towards referral for more detailed assessment of the vestibular and ocular systems when involved.

5. Vestibular-oculomotor rehabilitation

Studies and expert commentaries have supported the role of physical therapy and vision therapy in the assessment and rehabilitation of concussion patients since 2007 (Quatman-Yates et al., 2020). No longer a passive injury, concussion is considered a treatable injury. More active/targeted rehabilitation approaches for post-traumatic sequelae have better outcomes than prescribed rest alone (Collins et al., 2016).

5.1. Vestibular rehabilitation

Despite a lack of consensus on the optimal exercise program, multiple studies have demonstrated the efficacy of vestibular physical rehabilitation for individuals after mTBI (Alsalaheen et al., 2010; Alsalaheen et al., 2013; Gurley et al., 2013; Kleffelgaard et al., 2016; Murray et al., 2017; Prangley et al., 2017; Schneider et al., 2017). Vestibular rehabilitation is tailored towards the individual's impairments, and typically physical therapists work with the patient to improve balance, gaze stability, vestibulo-oculomotor function, canalith repositioning maneuvers if BPPV is present, and habituation exercises for specific head and body movements associated with that patient's daily activities/sport challenges (Bogle, 2019).

Of athletes receiving vestibular rehabilitation, 73% were returned to sport by 8 weeks post injury as compared to only 7% of those on a graduated exertion protocol (Schneider et al., 2014). Multiple studies have shown early evaluation (within 1 week) of pediatric concussion by multidisciplinary specialty clinics is associated with improved recovery times from concussion (Desai et al., 2019; Kontos et al., 2020). Rehabilitation targeting vestibulo-oculomotor impairments initiated within the first 10 days may be feasible and can be effective in reducing symptoms, time to recovery, and improving function (Reneker et al., 2017). At present, the median time for referral to vestibular rehabilitation ranges from 53 to 61 days after a concussion (Schneider et al., 2014). While early management is preferrable, it is estimated that upwards of 76.2% of acute concussions will present with post-concussion VOD (Ellis et al., 2015), and the majority of these cases, ~80%, will self-resolve within 4 weeks (Collins et al., 2015, & Ellis et al., 2015). Thus, it is imperative that when early intervention is not attainable, that persistent vestibular and/or oculomotor dysfunction(s) post-concussion that do not self-resolve within 4 weeks are referred for a more in-depth clinical evaluation and active treatment by trained rehabilitation providers.

It is never too late to refer a patient for vestibular and vision rehabilitation. Kontos (2018) assessed patients 18–60 years old with diagnosed intractable chronic mTBI (1–3 years of symptoms) with multiple tools including the VOMS and then prescribed progressive, targeted interventions and therapies (including vestibular and vision) that matched their mTBI clinical profiles and re-assessed 6 months. Following the initial assessment and intervention period, patients experienced significant improvements across symptom, cognitive, vestibular, and oculomotor domains. Specifically, patients experienced improvements in total symptom burden, verbal memory scores, smooth pursuits, VOR, VMS, convergence distance, and confidence in their balance from pre-to post-intervention (Kontos et al., 2018). In addition, other studies have employed an intensive eye and head exercise program with persons with chronic mTBI (> 6 months of symptoms) with resultant decrease in symptom severity and improvement in mental and physical health (Carrick et al., 2017).

VOMs can capture improvements over the course of vestibular physical therapy (VPT) when administered at initiation and termination of treatment. It should be noted that participants may still experience positive VOMS scores at the conclusion of therapy, however, these scores are often comparable to scores observed in a sample of adolescents without concussion (Alsalaheen et al., 2020).

To assess for vestibular function in more depth, physical or occupational therapists with advanced training and appropriate equipment are able to perform clinical tests such as dynamic visual acuity testing, head impulse test, head-shaking nystagmus test, and balance testing (Halmagyi & Curthoys, 1988; Harvey et al., 1997; Longridge & Mallinson, 1987). Videonystagmography (VNG) testing may also be helpful to assess vestibular function, which can be performed commonly by audiologists, otolaryngologists, otologists, and/or neurotologists with specialty training.

Persons with vestibular disorders who have phorias, tropias, or convergence insufficiency and had symptoms of visual vertigo require more time to recover (Pavlou et al., 2015). It is possible that ocular misalignment may also be a negative factor affecting recovery in persons after mTBI (Whitney & Sparto, 2019). Education on evaluation and treatment of the visual system is typically not part of an entry-level curriculum for physical and occupational therapists. However, with training some physical and occupational therapists can provide screening and/or assessment of visual function in conjunction with vestibular assessment. Trained therapists are highly capable of managing vestibular-related oculomotor issues but should refer to neuro-ophthalmology/neuro-optometry for refractory (non-improving) oculomotor dysfunction or atypical visual complaints. It should also be noted that vision therapy is considered the practice of optometry in some states, and physical and occupational therapists should be aware of state licensure restrictions in prescribing vision therapy without the co-management of a licensed eyecare provider in their state of practice.

5.2. Oculomotor rehabilitation

Of those with reduced NPC, many (up to 46% in some studies) (Storey et al., 2017), will recover with standard concussion clinical care and no intervention within 4.5 weeks of concussive injury, whereas those remaining with chronically reduced NPC require oculomotor and/or vestibular vision therapy for recovery (Storey et al., 2017; Santo et al., 2020). A reduced NPC is one of the many components needed to diagnose a true convergence insufficiency (CITTSG, 2008; Raghuram et al., 2019; Master et al., 2016; Gallaway et al., 2016). Recent studies on reduced NPC in VOMS testing of post-concussive patients has revealed that a reduced NPC was present in the majority of chronic (> 28 days) post-concussion patients, up to 89% (Raghuram et al., 2019; Merezhinskaya et al., 2019). However, only a small proportion, 8% of those patients had true convergence insufficiency alone, and the majority had concurrent accommodative disorders and/or other convergence deficits including convergence excess. This differentiation is important for the treatment of a reduced NPC.

There are clinical trials in the treatment of developmental (non-traumatic) CI that have compared the effectiveness of pencil push-ups, home-based vision therapy, office-based vision therapy, prism glasses, and placebo treatment options on true CI (Convergence Insufficiency Treatment Trial Study Group, 2008). These studies have shown improvement in CI with vision therapy. Comparison of developmental CI and post-concussive CI have shown differences in accommodative and vergence metrics, suggesting that post-traumatic CI may be a different clinical entity than developmental CI (Alvarez et al., 2021), and thus treatment strategies and response to treatment may differ in these groups. Recent studies have shown vision therapy to remediate reading and oculomotor difficulties in patients with mTBI,(Broglio et al., 2015; Ciuffreda et al., 2008; Gallaway et al., 2017;Thiagarajan et al., 2014) but further research is necessary to define the timing, duration, and exercises necessary for expedited recovery.

While VOMS is a validated screener for vestibular and oculomotor dysfunction post-concussion, VOMS is not a treatment strategy, and clinicians should be cautious in prescribing near push-ups for reduced NPC, as it could worsen oculomotor signs and symptoms if the patient does not have a true CI. This can be the case for some patients with an exophoria, who may use their accommodative convergence to maintain eye alignment if they have lost other types of compensating convergence from their TBI, which can trigger a resulting AS after prolonged near tasks (Satgunam, 2018, Shanker et al., 2012).

To appropriately treat patients with reduced NPC after TBI, patients with pseudo-CI must be distinguished from patients with true CI (Mazow et al., 1989). Since reduced NPC is not diagnostic of convergence insufficiency alone, a neuro-optometry referral is warranted for the thorough evaluation of vergence and accommodative status in patients who continue to have deficits chronically >4 weeks post injury, and/or whose symptoms worsen or plateau with convergence exercises. The authors caution clinicians when prescribing near push-ups for reduced NPC, as it could worsen oculomotor signs and symptoms if the patient does not have a true CI. It is crucial that a well-trained eye care provider like a neuro-optometrist, evaluate and differentiate the cause of a post-concussive reduced NPC to help guide vision therapy to tailor it to the specific oculomotor impairment. A neuro-optometry referral is warranted for evaluating accommodative status in patients who continue to have symptoms after convergence training or whose convergence is plateaued with training. While VOMS is a validated screener for VOD post-concussion, VOMS is not a treatment strategy.

Uncorrected refractive error, especially hyperopia, is an important consideration when diagnosing accommodation and convergence dysfunction. Low hyperopic to emmetropic refractive error were found in 81% of concussion patients (Raghuram et al., 2019). Uncorrected hyperopia which increases accommodative demand may contribute to accommodative insufficiency in many cases. Correction of other refractive errors such as astigmatism, even in minimal amounts, may assist in fusion and binocularity by creating a consistently clear retinal image (Dwyer & Wick, 1995).

Additional reasons to refer to neuro-opthalmology/neuro-optometry include the following: new differences in pupillary size, direction-changing nystagmus, overshooting with saccadic testing, saccades during vestibulo-ocular reflex (VOR) cancellation testing, head tremors, ptosis, a persistent head tilt, skew deviation, downbeating nystagmus, vertical diplopia, visual field cuts, a positive head impulse test, a positive head shake test, large convergence insufficiency, convergence spasm, or large phorias/tropias (Whitney & Sparto, 2019). Patients who had direct trauma to the eye and/or have other visual symptoms including but not limited to flashes of light, floaters, missing vision in one eye, eye pain, and persistent photophobia need to be referred urgently to an ophthalmologist/optometrist for comprehensive ocular health examination.

6. Ramifications of delayed care

In this emerging field, many questions remain regarding how to optimally care for children and adults after mTBI. Currently, return-to-sport protocols do not necessarily include criteria for normal vestibular or oculomotor function, however, they are clear signs of neurologic impairment. Until more is known, providers should require these domains of functioning to normalize before allowing patients to return to sport, due to the elevated risk of reinjury during sport participation with persistent deficits (eg, poor balance or gaze stability) and the consequences of chronic impairments from repetitive trauma to these brain systems (Mucha & Trobovich, 2019). With the increased association between vestibulo-ocular deficits following mTBI and increased risk of a prolonged recovery, athletic trainers have a crucial role in early identification of these impairments, and the utilization of VOMS can guide treatment and potentially decrease time missed from sport or activity (Bliss & Carr, 2020).

While optimal care is yet to be determined, it is of the utmost importance for individuals who sustain a concussion to receive early education and treatment. In pediatric patients presenting to the emergency department, those patients with delayed diagnosis of concussion had more medical visits during recovery, longer average time to symptom resolution, and were at nearly 3x higher risk of developing persistent concussion symptoms (Corwin et al., 2020b). In addition, persistent post-concussion symptoms can lead to severe health effects, including mental health issues such as such as anxiety, depression, suicidal ideation, (Mackelprang et al., 2014; Fralick et al., 2019) and overall decreased quality of life (Ayr et al., 2009; Swanson et al., 2017; Yeates et al., 2012), as well as an increased risk of musculoskeletal injuries following return-to-play from a concussion. (Howell et al., 2018a; McPherson et al., 2019)

Unfortunately, specific visio-vestibular assessments are often not regularly performed, particularly in the emergency department setting or primary care, and recommendations for vestibular-oculomotor related school and work accommodations are often not provided at the time of concussion diagnosis. Incorporating a standardized vestibulo-ocular assessment into practice could facilitate improved co-management of these patients to rehab providers who can provide rehabilitation as well as early targeted school/work accommodations and thereby improve return to learning/work for children and adults with concussion (Master et al., 2016).

7. Conclusion

Research supports comprehensive, multidomain assessment approaches for concussion. Accurate identification and early targeted interventions for vestibular and oculomotor symptoms are essential to improve recovery outcomes after concussion (Alsalaheen et al., 2013). Despite its limitations, the Vestibular/Ocular Motor Screen (VOMS) is an excellent tool that can aid clinical practitioners in identifying vestibular-oculomotor symptomatology, prompting referral to the proper providers (specialized physical and occupational therapists, and neuro-optometrists), thus leading to active, targeted rehabilitation for improved prognosis and recovery for patients who sustain mTBI.

Conflict of interest

The authors have no relevant financial or non-financial conflicts of interest to disclose.

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