The Role of Visual Sensory Performance Outcomes in Concussions: Impact on Concussed Special Operations Forces Combat Soldiers and Possible Implications for the Future of Sports-Related Concussions

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Abstract

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This thesis details the increased concern towards concussions in athletes and Soldiers as well as the role of visual sensory performance. More studies are showing the consequences, whether short term or long term, of concussions. The symptoms burden and multiple neurocognitive deficits faced by a concussed athlete are getting increasingly recognized by society, as well as healthcare professionals. Studies have shown how concussions can also cause visual sensory performance deficits, even when traditional assessments are normal, and the athletes are cleared to return to play. One big challenge with concussions is the lack of objective measures to diagnose a concussion, as well for medically clearing an athlete or Soldier to return to full activity. Even with the knowledge that visual deficits might be present after a concussion; most traditional assessments do not assess vision due to a lack of unified platform and test availability. Visual sensory performance is important for injury prevention and impact anticipation, as well as assuring peak occupational performance. We assessed US Special Operations Forces combat Soldiers' visual sensory performance outcomes. Concussions are the most common traumatic injury in the US military since 2000. Visual sensory performance outcome deficits could prevent Soldiers to complete their missions and impact their safety. Finding visual sensory performance outcomes deficits could help prevent an early return to play or return to duty, an increased risk of re-injury as well as help guide rehabilitation in athletes and military alike.

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Competing interests

Dr. Mihalik is the Chief Science Officer and holds equity interest in Senaptec Inc., the company that sells the Senaptec Sensory Station which was used to collect data for this study.

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Chapter I

Introduction

This thesis discusses the role of visual sensory performance outcomes in concussions. The literary review is composed of an introduction on concussion; from the pathophysiology to the different assessments used to diagnose a concussion and including deficits as well as potential risks. The literary review also includes information on visual sensory performance and highlights the importance of vision in sports and in the military. The potential consequences of visual sensory performance deficits due to concussions are also explained for both sport-related concussions and mild traumatic brain injuries in the military. Athletes and Soldiers need optimal visual sensory performance to complete their tasks and visual deficits can have negative impacts on their success. The literature review is followed by a manuscript. We compared visual sensory performance outcomes between Special Operations Forces combat Soldiers with and without a history of mild traumatic brain injury and further evaluated lifetime concussion incidence and recency among those reporting a history of mild traumatic brain injuries. Soldiers are often in high risk situations and assessing visual sensory performance outcomes deficits is important for the success of their missions. Lastly, there is an executive summary concluding the thesis which discusses future directions.

Literary Review

Concussions and Mild Traumatic Brain Injuries

With around 1.6 to 3.8 million of sport related concussions in the United States every year, concussions are a well-established injury in sports. In Canada, there were approximately 46 000 diagnoses for concussions in patients aged 5 to 19 years old in 2016-2017. Fifty percent of the 46 000 concussions were sport-related concussions.[1] This health issue has raised concerns from researchers, clinicians, sports associations, and athletes over the past few years. The incidence of sport-related concussions is higher in contact or collision sports.[2] Football and men's lacrosse have a higher rate of concussion compared to woman lacrosse and soccer.[3,4] A sport-related concussion is defined as a traumatic brain injury caused by biomechanical forces.[5]

These biomechanical forces will cause a complex pathophysiological process in the brain, creating a neurometabolic cascades.[6] The force can be both a direct or indirect hit to the head, and a linear or rotational force.[7,8]

Mild traumatic brain injuries (mTBIs) are the most common traumatic injury in the US military since 2000. In fact, 82.3% of all the traumatic brain injuries (TBI) sustained are mTBIs, making them the most common traumatic injury in the US military.[9–11] In 2020 only, 16 551 traumatic brain injuries were recorded, including 13 755 mild traumatic brain injuries.[10] This health issue has raised concerns from researchers, clinicians, military organizations, and Soldiers over the past few years. The incidence of mild traumatic brain injuries is higher due to the increased deployment of US Soldiers. Since 2001, around 1.3 million US military members have been deployed to Afghanistan and Iraq.[12–14]This increase is also due to better protective equipment to decrease the risk of traumatic brain injuries and deaths as well as the increased use of improvised explosive devices.[12,13,15] Even though the term 'concussions' is becoming more common, in the military setting, mild traumatic brain injury is most often used, due to the risk of traumatic brain injury and its classification. The United States Department of Defense characterizes four different degrees of traumatic brain injury as: (1) Mild traumatic brain injury/concussion: Confused or disoriented state which lasts less than 24 hours; or a loss of consciousness of less than 30 minutes; or a memory loss of less than 24 hours. (2) Moderate traumatic brain injury: A confused or disoriented state that lasts more than 24 hours; or a loss of consciousness of more than 30 minutes but less than 24 hours; or a memory loss lasting between 1 and 7 days; or one of the mild traumatic brain injury criteria as well as an abnormal CT scan of the brain. (3) Severe traumatic brain injury: A confused or disoriented state for more than 30 minutes; or a loss of consciousness of more than 24 hours; or a memory loss of more than 7 days; as well as an abnormal imaging of the brain. (4) Penetrating traumatic brain injury or open head injury: a head injury where the scalp, skull and dura mater are penetrated. This injury can be due to a high-velocity projectile or a low velocity object such as a knife or fragments from the skull fracture that are driven into the brain.[9]

Pathophysiology. A concussion is caused by blunt forces which will lead to a complex pathophysiological process in the brain, creating a neurometabolic cascades.[6] The forces can be both a direct or indirect hit to the head, and a linear or rotational force.[7,8] Following the hit, a complex cascade of neurochemical and neurometabolic events happen. The force to the head causes a stretching of the axon of the neuron, damaging the cell. The deformation causes an energy crisis, but a decrease in cerebral blood flow prevents the brain from receiving what it needs. Subsequently, the crisis causes an imbalance in ions, causing a 'short-circuit' of the networks.[16] Some symptoms may persist because of the metabolic changes and decrease neurotransmission.[17,18] The cascade causes an impairment of neurologic function and clinical symptoms (e.g. headache, nausea, fatigue, more emotional, anxious, blurred vision, etc.).[7] Neurons are more vulnerable to additional injury in that state.[16] Studies have looked at the window of vulnerability of the brain after a sport-related concussion, which is when athletes are more susceptible to repeated concussions. From those studies, the window of vulnerability is under 10 days after the initial injury.[6,19,20] If an athlete returns to play before being asymptomatic, or within this vulnerability window, they are at risk of a rare, but fatal condition named Second Impact Syndrome. This syndrome is when the brain swells quickly after the athlete receives a second concussion, before the resolution of the symptoms of the first concussion. Second Impact Syndrome can cause severe neurological impairment or fatality.[21]

A mild traumatic brain injury can also be caused by a blast exposure. This mechanism is the most common mechanism of injury encountered in deployed military members due to Improvised Explosive Devices (IEDs) and other explosives.[15,22] Even though this might not cause neuronal cell death, it can change some transmitter system.[15] A blast-related mild traumatic brain injury might disturb the axonal pathways, damage the capillaries in the brain and cause cavitations.[23,24] Due to the blast wave, intracranial pressure will change and create bubble formation. This is also due to the skull deformation with elastic rebound caused by the wave and is one of the most important factors causing cavitations.[25] In addition to this, different types of energy, such as electromagnetic energy, can disrupt the central nervous system. Moreover, because of the blast wave, there will be a blood surge from the torso to the brain, causing damage to the small blood vessels and to the blood-brain barrier.[24,25] Four mechanisms have been thought to explain how blast-related mild traumatic brain injury occur: (1) A rapid change in pressure happen in a very short amount of time, which could affect organ systems such as the central nervous system. (2) Blast debris such as shrapnel (pieces of bomb, shell, or bullet) cause focal bodily trauma, either penetrating or blunt impact injuries. (3) Acceleration of the body because of the blast and collides with solid surface which cause tissue shearing and diffuse axonal injuries within the brain. (4) Environmental factors such as toxic fumes, electromagnetic pulses, or radiation, which may injure the central nervous system or other organ system.[15,22] In most cases, the injury will be a result of a mixture of all 4 mechanisms.[22] In a study on the shockwave created by both high-level blasts and low-level blasts (artillery, shoulder-fired rockets or detonated breaching charges), as well as blunt forces, it was shown that blast-related mild traumatic brain injuries were associated with significantly more neurological symptoms than mild traumatic brain injuries caused by blunt forces only. Moreover, concussed Marines who worked in occupations with higher risk for repeated low level blasts were more likely to suffer persistent neurological symptoms after returning from deployment compared to those at low risk for occupational risk of low level blasts.[26]

Cognitive deficits and neuropathology. Researchers are worried about long-term consequences of mild traumatic brain injuries, sub-concussive injuries, and repetitive head injuries.[2] Sub-concussive injury is defined as a traumatic impact to the head that transfers energy to the brain and injures axonal or neuronal integrity[18] even though it does not result in any immediate clinical symptom, which is similar to the low-level blasts.[19,26] Even though sport-related concussions are not the same as blast-related mild traumatic brain injuries, both traumas could share common pathogenic variables.[23] A lot of research has been done on athletes to look at the long term consequences of brain injuries. Studies have found that athletes can sustain thousands of sub-concussive hits to the head during a single season[27,28] which could be an indicator of repetitive neurotrauma.[29] However, the effects of those impacts are still unknown due to the lack of studies on sub-concussive hits and the lack of agreed biomechanical features and thresholds that are qualified as a sub-concussive hit.[18,30] Even though research is still evolving, advancements showed that retired NFL football players had mild cognitive impairments, neuroimaging abnormalities and differences in brain metabolism disproportionate to their age.[18] Autopsies also showed an accumulation of p-tau that was not related to normal ageing.[18]

The possible long-term cognitive effects of sports-related concussions have mostly been studied in retired American football players.[31] Retired players who sustained 3 or more sport-related concussions during their career had a five times greater risk of mild cognitive impairment diagnosis before the age of 50 years old compared to those with no prior sport-related concussions[18,31] and an increase by 3-fold in significant memory problems.[31] NFL football players were also more at risk of developing Alzheimer's disease and amyotrophic lateral sclerosis compared to men in the general population.[18] Studies also observed different neuropathologies, such as frontal and temporal lobes atrophy, thinning of the hypothalamic floor, shrinkage of the mammillary bodies, pallor of the substantia nigra, hippocampal sclerosis and reduction in brain mass; enlarged ventricles and, cavum septum pellucidum with or without septal fenestrations.[18,32] Retired football athletes also had a significant cortical thinning of the anterior temporal lobe as well as the orbitofrontal cortex which caused a lower cognitive performance.[18]

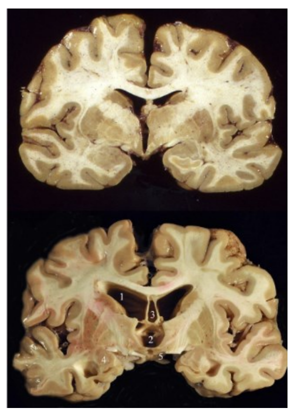

Figure 1. Difference in cerebral cortex and ventricles volume between a normal brain and a case of advanced CTE. (1) and (2) show dilatation of ventricles, (3) shows the thinning of the cavum septum pellucidum, (4) shows the atrophy of the medial temporal lobe and (5) shows the reduction of the mamillary bodies (R. A. Stern et al. PM&R (2011))

As for more of the microscopic neuropathologies, autopsies showed the presence of localized neuronal and glial accumulations of p-tau, as well as multifocal axonal varicosities involving deep cortex and subcortical white matter.[18] The accumulation of p-tau found post-mortem is also known as Chronic Traumatic Encephalopathy (CTE), but because there is no validated clinical criteria for CTE, there is no accepted method to diagnose a living person with CTE.[16,18,19] Military Veterans are also at risk to develop those neurological disorders as well as Lewy body disease, an abnormal deposit of alpha-synuclein in the brain, and motor neuron disease.[23,33] It is also thought that an increased number of mild traumatic brain injuries increases the risk of developing Post-Traumatic Stress Disorder (PTSD) in the US military.[24]

A proper assessment and recognition of a concussion is critical. Not recognizing a concussion or sending an athlete too early to return to play may increase the risk of neurological deterioration and prolonged return to play due to a possible cumulative effect of head impact. As for active service members with an unrecognized acute mild traumatic brain injury, they expose themselves as well as their team members to further injury or death in a combat setting. Service members could have a harder time to recall or relay information, identify threats, or make a rapid decision.[15] Symptoms, even if not present at first, can be delayed or evolving, which explains why a concussion diagnosis can be hard to do. Service members and athletes with a suspected concussion should be removed right away from the field and reassessed later.

Visual and Sensorimotor Skills

Sensorimotor skills are important to detect stimuli, direct our attention to the information and move our bodies to react successfully in a dynamic environment.[30,34]Being able to process the relevant visual information and respond with the correct motor response is crucial.[34] Visual information processing is used at all times, whether someone is driving, stepping off the sidewalk or playing sports.[35] Vision is needed to recognize potential dangers and anticipate.[2] All of this process is partially due to our vestibulo-ocular system, comprised of both the vision and the vestibular system, which relays information so we can position our body and head to keep both visual and balance control.[30,34] The vestibular system, which gives information about motion, head position and spatial orientation, is composed of the small sensory organs in the inner ear and has connection to the brainstem, the cerebellum, the cerebral cortex, the ocular system and the postural muscles.[36] The vestibular system is composed of two different units: the vestibulo-ocular system, which is for visual stability during head movement, and the vestibulospinal system, which is for postural control.[36] Those two functional units, even though they seem similar, do not share the same neuronal circuit, which means one unit can be affected, but not the other.[36] Visual sensory performance refers to the ability of the brain to receive sensory information from the eyes, combine that information with somatosensory and vestibular inputs, and then produce an appropriate motor response.[7]

The different connections to the brainstem, the cerebellum, the cerebral cortex, the ocular system, and the postural muscles can be complex and are the reason for different domains of vision. Some components of different domains of vision are saccades, smooth pursuits, accommodation and vergence. Saccades are the rapid eye movements that redirect the gaze from one object to another; primarily directed towards stationary targets whereas smooth pursuit is to track moving targets.[37–39]Accommodation is to look at different objects that are at a different distance. The eye needs to curve the lens so the object can focus on the retina.[40] As for vergence, it is the ability to turn the eyes inward and outward to look at objects at different range.[41] One example on how complex the connections are in the brain for the vestibular-ocular system is a study on short term memory, vergence and saccades. This study showed that the dorsolateral prefrontal cortex, the anterior and posterior cingulate, as well as the ventral lateral prefrontal cortex are involved in predictive and short-term working memory tasks during oculomotor predictive movements.[41] Predictive movements in the visual system is used by the brain to reduce latency. Predictive behaviors have been seen in saccades, smooth pursuits and vergences. Those behaviors are influenced by previous visual stimuli, which shows that working memory is also used during predictive movements. The dorsolateral prefrontal cortex was a shared area for both vergence and saccadic networks.[41] This study suggested that even though we generally think that vision is primarily located in the occipital lobe of the brain for the visual cortex, there are a lot more connections and areas of the brain that are associated with vision. In another study, researchers wanted to look at the difference in static and dynamic balance between participants with normal vision and participants with low vision. During static balance, participants who had a normal vision score but closed their eyes had an increase sway on foam pads and during unilateral stance.[42] Moreover, during dynamic balance, participant with a worse vision score had an increase step width (11 cm compared to 7.36cm, $p<.001$) and an increase time (12.2 cm/sec versus 16.45 cm/sec, $p< .004$), compared with participants who had a normal score for vision.[42] Participants with a lower vision score were more careful when they walked to increase their kinesthetic information and compensate for an incomplete visual feedback. The study showed that vision plays an important role during walking for postural control by using visual proprioception, where vision is used to relay information about someone's body movements in relation to the environment. In other words, the interaction between both the central nervous system, the muscles sensory system and the peripheral sensory systems is crucial for adjusting balance and sensory maps.[42]In another study on impaired eye tracking after a sport related concussion, researchers found that the participants who sustained a concussion had a slower gait speed compared to the control group. A possible explanation is that the participants adapted a conservative gait strategy to decrease their risk of injuries. Those participants also had abnormal vergence, and the researchers explained that physiological control for eye movements and postural movements have the same foundation, which could mean that if someone has vision deficits, they are most likely to have motor deficits too.[43]

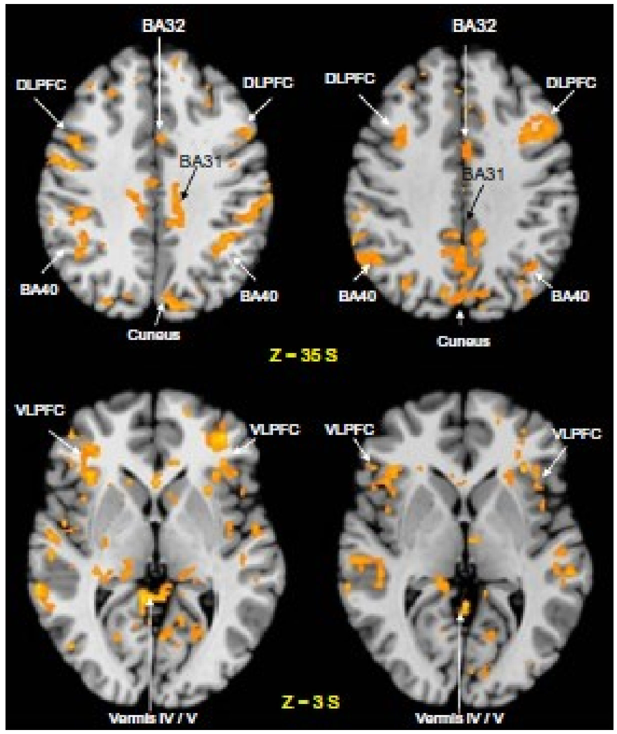

Figure 2. Location of the dorsolateral prefrontal cortex (DLPFC), parietal eye field (PEF), ventral lateral prefrontal cortex (Alvarez et al., 2010)

A lot of studies looked at vision in sports. Some studies have examined the difference between the visual performances of elite athletes, amateurs, and non-athletes. In elite sports, there is evidence to suggest elite athletes have better visual performances than less successful athletes and non-athletes.[44] In a study on differences in visio-spatial intelligence, which is the ability to perceive, analyze and understand the visual information around them, they observed differences between rugby players and non-athletes. Rugby players were 93% more proficient in speed of recognition, 23% better in hand-eye coordination. 19% better with saccadic eye movements, 15% better in peripheral awareness and 9.59% better in accommodation facility.[45] In another study on vision, basketball players had a near point of convergence of 4.66cm and the sedentary participants had one of 6.24cm, with a p value of .004.[46] Those studies show how athletes will have better visual scores compared to non-athletes. The visual skills identified as important for success in sport include static and dynamic visual acuities, contrast sensitivity, depth perception, accommodative-vergence facility, perception span, central eye-hand reaction, and response speed.[19,44]

However, a lack of data and assessments is seen due to an absence of standardized assessment techniques for some skill and of commercial instruments specific to athletes.[44] An eye care professional will evaluate ocular health during a vision examination, however, there is the need to add the processing skills of the athletes, the sport-specific demands as well as visual efficiency.[47] Moreover, comparing scores post-concussion with a generic baseline could be invalidated due to the presence of sport-specific trends.[48]As it was mentioned earlier, athletes have better visual skills than non-athlete, which means athletes' scores will be higher when compared to a generic baseline. Moreover, sport-specific trends are important to keep in mind. Different sports or positions will require different visual abilities. Athletes need to be able to assess the play, the position of their teammates and opponents within a few seconds. To hit or catch a ball in baseball, you need to be able to move a bat or hand to the right place at the right time.[49] A baseball player will need to be able to track the ball, using visual acuity, depth perception, eye-hand coordination and reaction time.[50] One the other hand, a hockey player will need to use more their accommodation and convergence skills to track the puck, the puck carrier, and the other players. Hockey players also need to have a good depth perception, reaction time and a fast span of recognition.[51] Different positions in the same sport may also require different visual skills. In football, a quarterback needs to have a good depth perception, eye-hand coordination but also a fast span of recognition to be able to process the information from the play quickly to react properly. A receiver will need to have good accommodation and convergence skills to be able to always concentrate on the ball and a good depth perception skill to analyze where to place themselves to receive the ball.[52] Two sensory stations have been developed in the past years to tackle those limitations: Nike SPARQ Sensory Station and the Senaptec Sensory Station, the SPARQ being the precursor of the Senaptec sensory station.[53] Those sensory stations provide a unified platform allowing perceptual and visual-motor abilities to be tested.[35] The Senaptec Sensory Station analyzes 10 different domains of vision and compares the results within each sport and players' position. They can be separated in 3 types of tests: visual sensitivity tests (visual clarity, contrast sensitivity, depth perception and target capture), Eye-quickness test (Near far quickness, dynamic visual acuity) and visual-motor control tests (perception span, hand reaction time, go/no-go, and eye-hand coordination):[35]

Visual Clarity. This domain measures static visual acuity, which is a critical foundation for sports vision and test the minimum detectable spatial resolution for an object that is not moving.[35,44] Static visual acuity is usually measured using the Snellen chart, where the patient has to read aloud the line of letter until they cannot anymore. Each line of letter becomes smaller. A normal result would be 20/20 vision. It can be affected if participant wears contact lens that are not properly fitted.[44] Static visual acuity is at the base of the sport vision pyramid, meaning that if deficits are found in visual clarity, the other domains of vision will probably have deficits too.

Contrast Sensitivity. This is used to detect the contrast in backgrounds, and it is important to recognize objects and faces under varying lighting conditions.[44,54] Athletes or Soldiers can't control the glare light coming from the lights or the sun. If the glare light is intense and close enough to the target, the contrast will decrease and it will be hard to see the target, for example when a tennis player can't see the ball because of the sun.[55] Contrast sensitivity is usually measured with the Pelli-Robinson letter chart, where the participant's ability to read a letter aloud to the examinator is assessed. The letters have different contrast and the test ends when the participant cannot read the letters aloud correctly.[56] A poorer contrast sensitivity was highly correlated with driving performances.[56] In another study, results showed that a reduced contrast sensitivity among older women was observed in patients with mild cognitive impairments and could predict the development of dementia over a 10-year study. A lower score in contrast sensitivity was also associated with worse cognitive performances at the end of the study.[57]

Depth Perception. This domain is the ability to determine the distance and spatial localization of an object.[44,54] Athletes with better depth perception, also known as stereopsis, are better with spatial and temporal placement. In baseball, athletes who scored better in a stereopsis test were better at catching the ball. However, athletes with a lower stereopsis made more temporal errors.[58] An athlete or a combat Soldier need to be able to judge the depth to help anticipate properly any collisions, passes, or threats.

Near Far Quickness. The Near Far Quickness is the ability to change focus quickly, looking at far, middle, or near objects. Athletes need to quickly adjust, and it is important for making timely decisions, looking at teammates, opponents, or other objects.[44,54] Near far

Quickness is important because this test looks at near point convergence. After a sport-related concussion, convergence insufficiency is common in athletes even one month after the initial injury. In a study on near point convergence, researchers found that approximately 42% of the athletes still had convergence insufficiency within one month of their concussion and that athletes who had a worse convergence insufficiency had more neurocognitive impairments as well as increased symptoms compared to the athletes who had a normal near point convergence.[59]

Perception Span. The Perception Span is also known as the central visual recognition accuracy. It measures speed and span of recognition, which can help make quick decisions, as an athlete or a Soldier need to receive and synthetize information rapidly to perform well.[44,54]

Multiple Object Tracking. The Multiple Object Tracking is crucial for spatial awareness and proper movements.[54] For example, a football player needs to quickly decide who to pass the ball too while being aware of his teammates position as well as his opponents' positions that are always changing. Multiple Object Tracking is important for situational and spatial awareness where everything moves and changes.[60]

Reaction Time. It is the time passed between the onset of a visual stimulus and the initiation of a motor response.[44] In other words, reaction time is to measure how quickly can a participant respond to a stimulus. Reacting quickly to visual input is important in sports as it can be crucial for both sport performance or to avoid injuries (e.g., A fencer that needs to react quickly to their opponent).[54] Reacting quickly is also important in the military to protect themselves and complete their tasks.

Target Capture. Target Capture assesses the coordination between peripheral and central vision. It is the ability to find and identify a peripheral target, which is important to ensure that all important information is observed.[44,61]

Eye-Hand Coordination. Responding to visual input is a fundamental to interact properly with the world. Eye-Hand Coordination test is important for peripheral eye-hand response. In other words, how quickly and accurately hands move to respond to a visual stimulus, whether the stimuli are in the central or peripheral vision.[44,61]

Go/No-Go. Go/No-Go looks at the ability to inhibit motion in response to a new stimulus or information. Inhibition would help prevent mistakes and potential injuries.[44,61]

Some elite athletes will also have certain visual-perceptual abilities that are enhanced, for example Dynamic Visual Acuity (DVA), compared to the normal population.[35,44] In a study comparing athletes versus nonathletes, the researchers wanted to see if athletes could be differentiated from nonathletes in their capacities to access a wider range of both visual, ocular, and motor skills compared to nonathletes. Athletes had a mean of 426.9 in contrast sensitivity, which was better than nonathletes who had 346.4 ($p=.006$).[62] For near point convergence, athletes had a mean of 6.55 cm whereas nonathletes had a mean of 3.76cm ($p<.001$); athletes were more likely to have their near point convergence between 6 and 8 cm, and nonathletes closer to 4 cm.[62] Moreover, for dynamic visual acuity, athletes had mean of 0.21 for their dominant eye, compared to 0.36 in nonathletes ($p=.03$).For accommodative facility, athletes had a mean of 30.3 letters and nonathletes 27.2 letters ($p=.043$).[62] Athletes that are in interceptive sports have superior visuomotor skills compared to nonathletes. Athletes also have a wider access to various visuo-oculomotor abilities, which allows athletes to coordinate visual and oculomotor abilities more effectively under demanding conditions.[62] Vision is a learned complex and a developed set of functions including many skills.[47,63] The fact that athletes have a wider access is due to years of training specific visual skills while playing their sports.

Each domain of vision is important. If one is not optimal, the others will not work efficiently. An easier model to visualize this is the Sport Vision pyramid, where each level needs to be stable, or the pyramid will not be stable. If, for example, the monocular vision does not function properly, the binocular vision will not be optimal either.[64]

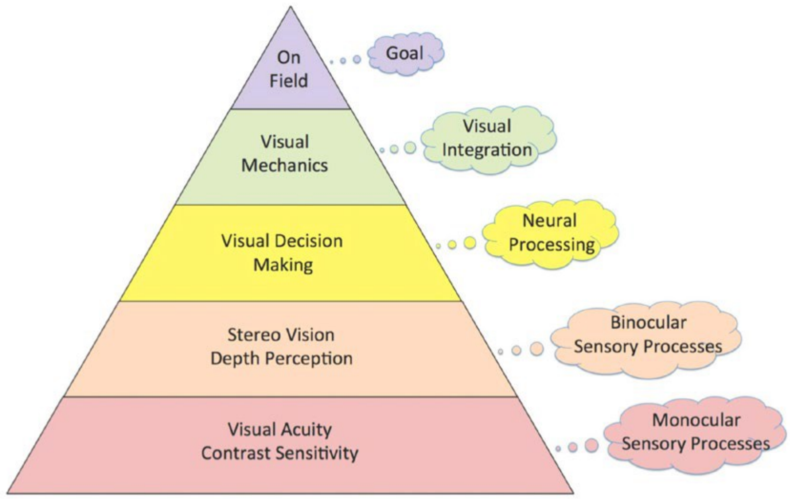

Figure 3. Sport Vision Pyramid showing the importance of each component of vision (Laby et Kirschen, 2018)

The test-retest reliability is stable for the visual clarity test, the contrast sensitivity, depth perception, perception span, target capture and response time. A normal learning effect of motor response has been found in the Near-Far Quickness test, and the eye-hand coordination test and Go/No-Go test.[35,44] The validity of the visual clarity test and the contrast sensitivity test have been cross-validated.[2,35,44]Some studies looked at visual and sensory performances to see if they were linked to game performance.[7,35,65] In a study done by Poltayski et al., 2014, researchers linked a better performance in a few tests (perception span, near-far quickness, go/no-go, and hand reaction time) to 69% of variability in goals scored.[35,65] The variability in goal scoring shows that visual and sensory performance can impact performance, but also how a player reacts to imminent head impact.[7] Another study also looked at visual performance and its role in injury prevention. When vision was eliminated in resistance training, there was a decrease in the lower body power.[66]

Many factors can influence the scores for perceptual and visual-motor performance. Sex differences, individual's psychological state (stress, anxiety, negative emotions) and circadian rhythm are all important factors to consider. Peak cognitive performance was usually between 16:00 and 22:00 and being awake for a longer time before doing the tasks.[35]

Mild Traumatic Brain Injuries and Visual Deficits

Even though cognition and neuropsychological changes are important factors and consequences to look at, a lot of the literature is already studying those changes. However, not many studies look at the visual deficits after a mild traumatic brain injury and the effects that it can have on the return to duty, injury prevention and rehabilitation.[29] Vision is important to assess because 60% of athletes with a sport related concussion will experience symptoms from their vestibular and ocular systems.[36] Athletes that sustained a sport-related concussion had impaired saccadic functions, convergence abnormalities, decreased visual accuracy and found it hard to keep visual attention.[30] In a retrospective study on visual dysfunction as a predictor of mild traumatic brain injury in US military veterans, they observed visual dysfunction in 68% of the participants, almost six years after injury.[67]

After a concussion, the eyes ability to work together, in terms of depth perception and dynamic visual acuity, might be weakened.[30,68] Moreover, some athletes who were cleared to return to play still had deficits in a few tests, meaning that their brains could still be more vulnerable to injury and neurological deterioration.[7,16] One of the main indicator to be clear to return to play or return to sport is the resolution of symptoms.[43] During a study by Harpham et al. (2014), two of their subjects sustained concussions during their data collections. The researchers found that even though that the subjects had no more symptoms, their computerized neurocognitive tests and postural tests results were comparable with their baseline scores, the participants still had deficits. One participant had 55% deficits in contrast sensitivity, 44% in depth perception and 10% in near far quickness. The second participant had a deficit of 32% in contrast sensitivity, 6% in near far quickness and 16% in perception span. Those results could be due to the concussion, but also to poor tackling technique. Either way, those results show that, even though an athlete can feel ready to back to play, they might still experience some visual sensory deficits.[7] In another study by Day et al., the researchers looked at the results of neurocognitive testing after the resolution of the symptoms of a concussion in the participants. At the end, 38% of the athletes still had some neurocognitive deficits even when they were not experienced symptoms.[69] Moreover, in a study on near point at convergence in athletes after sustaining a sport related concussion, 40% of the participants still had convergence insufficiency even a month after the initial injury.[59] Those results show that even if athletes don’t experience symptoms, they might still have visual deficits. Right now, for the return to play, the progression is mostly based on symptoms provocation during each stage. If an athlete does not have any symptoms and is cleared to return to play, they could still have some visual deficits, which makes them more at risk of another injury and possibly more neurocognitive deficits.

Visual symptoms have been associated with a longer recovery after a sport related concussion as well as with persistent concussion symptoms.[43]Dizziness, which is a symptom that is caused by abnormalities in the vestibular and in the visual systems, could be a predictor of a longer recovery. In a study where researchers observed which on-field sign and symptoms could predict a prolonged recovery, they found that dizziness was associated with a 6.34 odds ratio of a prolonged recovery from a concussion.[70] In average, the participants' prolonged recovery was approximately 29.61 days. The only significant risk factor found for a prolonged recovery was dizziness, which could be due to vestibular deficits.[70] Moreover, in another study on near point convergence, researchers found that participants who had convergence insufficiencies performed worse during reaction time testing, verbal memory, visual motor speed and participants also suffered from more symptoms compared to the control group. Normal near point convergence is usually under or equal to 5 cm. For the study, the researchers separated the participants in two groups: a control group and a convergence insufficient group. The control group had an average of 1.53 ± 1.53 cm for their near point convergence. The convergence insufficient group had an average of 12.64 ± 8.97 cm. The control group had a total symptom score of 24.04 ± 19.48 and the convergence insufficient group had a total symptom score of 35.94 ± 24.98, the two groups being statistically different. When participants had worse near point convergence, they had more symptoms on the symptoms scale. Researchers explained that participants could have a more severe injury or damages, which would explain why they had worse symptoms. Researchers also explained that it could be because there are many visually based symptoms related to convergence insufficiency that overlap with items on the symptoms scale.[59] Abnormal scores during eye tracking tests were also related to an increase in concussion symptoms, as well as a prolonged recovery when symptoms were provoked doing vertical saccades and vertical vestibular ocular reflexes, which is the ability to stabilize an image on the retina while the head is moving.[43,71] In a study on impaired eye tracking after a concussion, researchers found a significant association between BOX scores, a measure of unpaired pupillary movement, and post-concussion symptoms scale scores. Oldham et al. separated the participants in three groups: a concussed group with abnormal BOX scores, a concussed group with normal BOX scores and a healthy control group. The concussed group with abnormal BOX scores had a total post-concussion symptoms score of 51.1 ± 16.3 and a BOX scored of 15.9 ± 3.6 compared to the healthy group that had a total symptoms score of 3.7 ± 8.6 and a BOX scored of 7.8 ± 5.6.[43] Those results mean that participants who had impaired eye tracking also had more symptoms or worse symptoms' severity than the healthy control group. The concussed group with abnormal BOX score also had worse symptoms and a worse BOX score than the concussed group with normal BOX scores (51.1 ± 16.3 compared to 31.4 ± 8.6 for symptoms respectively and 15.9 ± 3.6 compared to 4.7 ± 3.0 for BOX scores).[43]Those results show that symptoms severity could be worse due to eye tracking deficits in a concussed population. The precise mechanism as to why there could be vestibular and ocular deficits is not well known due to the complex connections in the brain.[71] However, it is thought that a concussion causes an injury to the peripheral vestibular apparatus and the brainstem nuclei or the central processing structures, which results in the inability to properly process sensory inputs.[72]

A study by Miyashita et Ullucci (2020) noted a small correlation with cumulative head impacts with higher average rotational acceleration and vestibulo-ocular deficits.[30] Athletes that sustained more head impacts had a greater increase between their preseason and postseason perception scores (r=0.54, P<.001; preseason 25.76 ms, postseason 26.97 ms). Moreover, their dynamic visual acuity scores on their right side decreased with maximum rotational acceleration (r=0.36, P= .04; 4.15% preseason, 6.67% postseason).[30] A decrease in visual perception can increase the risk of injury and decrease one's performance.[30] In other words, a vestibulo-ocular dysfunction may predispose an athlete to further injuries. Anticipation and visual performance may influence the severity as well as the frequency of head impact.[2] If an athlete is not able to anticipate a contact, they will not be able to avoid it or brace themselves, which increases the risk of injury, but also the risk of a higher average rotational acceleration of the head,[2] causing more damage.

The clinical research findings from the long-term impact of military-relevant brain injury consortium showed that military personnel who have a history of mild traumatic brain injury had greater retinal nerve fiber layer thinning, a greater decline in visual field, and a decline in high spatial frequency contrast sensitivity.[73] In another study with military veterans, Bulson et al. observed that 50 to 75% of the veterans with a history of mild traumatic brain injuries complained of vision symptoms such as accommodative problems, blurred vision and photosensitivity.[74]

Mild traumatic brain injury clinical diagnosis. Diagnosing a concussion in general is difficult due to the lack of objective measures and biomarkers. However, it is sometimes harder to diagnose a mild traumatic brain injury in the military to the potential of multiple injuries, sometimes life-threatening, and the situation the service members are in (i.e., In-theater, safe space, mission).[15,22,75,76] Usually, concussions are diagnosed depending on the mechanism of injury, the symptoms that the athlete presents with and with a balance assessment. Diagnosis also relies a lot on the clinicians' interpretation of the sign and symptoms of the athlete. In multiple studies, participants are classified in the concussed group depending on the mechanism of injury and if they experience at least one of the possible signs and symptoms of a concussion.[59,77,78] For example, in a study by Pearce et al. (2015), concussion diagnosis was defined as having more than one sign or symptom of a concussion at the time of injury, ongoing signs and symptoms following the hit and a mechanism of injury that could be a risk to have a concussion.[59]

In the US military, mild traumatic brain injury is also challenging to diagnose. Often, blast exposure results in multiple injuries, some of them potentially life-threatening, which hinders concussion diagnosis. Moreover, combat Soldiers tend to not report symptoms of a concussion, even though the injury might increase risk of injuries to the service members and their team.[15] To help destigmatize reporting symptoms or a concussion diagnosis, the Department of Defense created a standardized process to identify and manage mTBIs, which is an event-based screening.[15,22] All military personnel who were within 50 meters of a blast exposure or a potential concussive event need to get immediate screening. They will have a mandatory 24-hour rest period as well as a concussion evaluation after the potentially concussive event and once service members are in a secure location. All the military personnel close to the blast will be re-assessed after the rest period, if they don't have any symptoms, the Soldiers are cleared to return to duty. However, if they have symptoms or a poor score on their concussion assessment, service members will start the progressive return to activity, depending on their mTBI history. If they have a history of 2 mild traumatic brain injuries within 12 months, Soldiers must be asymptomatic for 7 consecutive days before going through the return to duty stages. If a Soldier had three or more concussions within the past 12 months, they will be referred to a higher level Concussion Specialty Care Center for a comprehensive recurrent mild traumatic brain injury assessment.[22]

Each concussion is different, and the symptoms vary depending on the individual[2], as well as the length of recovery. Some individuals present with one or more symptoms like a headache, retrograde or anterograde amnesia, irritability, sleep disturbances, sensitivity to light or noise, slowed reaction time, tinnitus, blurred vision, or even loss of consciousness. The combination of symptoms is different with everyone as well as the intensity of each symptom. The symptoms may last from a few days or a few weeks to months after the injury.[5] To try and prevent an early return to play and identify concussions more easily, the Return-To-Play progression and Sport Concussion Assessment Tool 5 were created, which are widely used by athletic trainer.[78,79] In the US military, they created a Progressive Return to Activity and the Military Acute Concussion Evaluation.

The Return-to-Play progression has 6 different stages. The progression should start only when the athlete reports being asymptomatic and has a normal clinical examination. Each stage should be separated by at least 24 hours, but if symptoms appear at any stage, the activity should be stopped and restarted 24 hours later. The first stage is being asymptomatic while no activity, the second stage is light exercise, the third stage is some sport-specific drills without any risk of contact, the fourth stage is noncontact training and resistance training, the fifth stage is unrestricted training, and the sixth stage is a full return to play. The timing for the return-to-play is case dependent.[79] In a study on professional rugby union players, researchers looked at the incidence of concussion, the different clinical outcomes and the following injury risk after a concussion. The mean number of days spent at each stage of the return to play progression were 3.5 days for stage 1, 1.3 days at stage 2, 1.4 at stage 3, 2.0 days at stage 4 and 1.0 days at stage 5. All the participants had to complete neurocognitive tests at stage 4 and could not progress to the next stage if their results did not match the baseline results. Some players did not meet their baseline scores, others declared symptoms during the test and others became symptomatic at stage 4, which explains why the number of days increased at stage 4. Those results show that even if the majority of symptoms resolved within 7 to 10 days, some injury resolutions can be more complex and diverse, with 38% of their players reporting a recurrence of symptoms during stage 2 to 5 and not meeting their baseline scores during the neurocognitive tests.[80] Researchers also found that players who returned to play had a 60% greater risk of sustaining an injury in their season compared to athletes who did not sustain a concussion in the same season, which is also why they suggest a longer and more comprehensive return to play progression for concussed athletes.[80] Even if the Return-To-Play Progression stages is a step in the right direction for recovery, this progression still has some challenges. The duration of the stages can be different between athletes due to different recovery length and the variability between athletes. The Return-To-Play Progression lacks individualization for the athlete, which is why a more comprehensive progression could be better.

Stage[a]	Physical Activity
1	No activity
2	Light exercise: <70% age-predicted maximal heart rate
3	Sport-specific activities without the threat of contact from others
4	Noncontact training involving others, resistance training
5	Unrestricted training
6	Return to play

[a] Stages should be separated by at least 24 hours.[7]

Figure 4. Return-To-Play Progression stages (Broglio et al., 2014)

The Progressive Return to Activity also has 6 different stages with an increased intensity at each step. However, before full clearance to return to unrestricted activities, Soldiers need to complete the Return to Duty Screening at stage 5, which consists of a physical exertion test and a neurocognitive test using the Automated Neuropsychological Assessment Metrics (ANAM). When Service Members are resting after their diagnosis, they also receive education and counseling on concussions to help reassure warfighters that concussions and their symptoms are not a permanent disability. Moreover, because service members already have an abnormal sleep cycle due to their mission or work shifts, they receive a Warfighter Sleep kit that contains a sleep guide, sleep mask, ear plugs and a DVD with relaxing images and sounds.[22]

E. Stages of the PRA: Instructions for Progression (Continued on next page)

Stage	Objective	Environment	Physical/Vestibular Activity	Cognitive/Oculomotor Activity	Restrictions Stages 1-5
Stage 1*: Relative Rest	Avoid symptom provocation, and rest to promote recovery	▪ Minimize light and noise ▪ Stay home/ in quarters	▪ Daily activities that do not provoke symptoms ▪ Limit large or sudden changes in head position ▪ No exercise	▪ Limit screen time as needed to avoid symptom provocation ▪ Very light leisure activity (e.g. reading, television, conversation)	▪ Do not go outside the wire in a combat zone
Stage 2: Symptom-Limited Activity	Introduce and promote mild exertion	▪ Calm and familiar environment with limited distractions	▪ Limit large or sudden changes in head position ▪ Light routine exertion (e.g. walking on even terrain, light household chores, stationary bike) ▪ No weight or resistance training	▪ Simple, familiar activities performed one at-a-time (e.g. routine computer use, leisure reading)	▪ Maintain or reduce pre-injury levels of caffeine/energy drinks and nicotine
Stage 3: Light Activity	Introduce occupation-specific exertion and environmental distractions	▪ Introduce environmental distractions during activity ▪ Return to work on limited duty/profile without significant symptom provocation	▪ Initiate tasks requiring changes in head position ▪ Light aerobic exercise without resistance (e.g. elliptical, stationary bike, walking on uneven terrain) ▪ No lifting > 20 pounds ▪ No resistance training	▪ Simple, unfamiliar tasks or complex familiar tasks (e.g. grocery shopping, technical reading)	▪ No alcohol** ▪ No combatives or contact sports***
Stage 4: Moderate Activity	Increase activity intensity and duration	▪ Distracting or busy environment during activity as tolerated	▪ Attempt tasks requiring more significant or sudden changes in head position ▪ Increase intensity and duration of activities (e.g. non-contact sports, hiking or running, push-ups, sit-ups) ▪ Introduce resistance training as tolerated	▪ Increase intensity and duration of activities (e.g. navigate busy environments, recall and follow complex instructions)	▪ No driving until visual and vestibular symptoms have resolved
Stage 5*: Intensive Activity**	Introduce exertion of duration and intensity that parallels service member's typical role ▪ Complete RTD Screening prior to advancement to Stage 6	▪ Typical daily environment EXCEPT listed restrictions	▪ Resume pre-injury exercise routine and training activities	▪ Complex problem solving or multi-tasking with exertion or distracting environment	▪ No weapons fire or blast exposure***
Stage 6: Return to Full Duty	Return to pre-injury activities	▪ Typical daily environment	▪ Unrestricted activity		

* Ensure SM adheres to Relative Rest guidelines and attempts to increase activity within 72 hours to avoid potentially detrimental effects of prolonged rest
** Alcohol use can exacerbate post-concussive symptoms of headache, depression, and anxiety and can cause impaired cognitive functioning, dehydration, and sleep disturbances
*** In Stage 5 the SM may gradually increase exposure to high risk activities in a *supervised* training environment based on mission requirements

Table 1. Return to Duty stages (Military Health System, health.mil, 2021)

The Sport Concussion Assessment Tool 5 has three components: symptoms, cognition, and balance. Symptoms are assessed using the Symptoms Scale from the Sport Concussion Assessment Tool 5 (SCAT-5). The symptoms can be separated in different categories: somatic (e.g., headache), cognitive (e.g., feeling like in a fog), emotional (e.g., rapid, and exaggerated changes in mood), behavioral changes (e.g., irritability), and cognitive impairment (e.g., slowed reaction time).[5] Vision has been linked to headaches, dizziness, light sensitivity, impaired saccades, and convergence abnormalities.[19] However, those symptoms can also be non-specific to a concussion, which means that only the symptoms cannot diagnose a concussion but can help suspect one as a differential diagnosis.

Cognition is assessed during the sideline evaluation by using a short neuropsychological testing battery to assess both attention and memory deficits in the SCAT-5. Those tests are the Maddocks' questions and the Standardized Assessment of Concussion. The Maddocks' Questions are questions to quickly assess the retrograde memory, the ability to recall past events that occurred before the concussion, in an immediate sideline assessment after a suspected sport-related concussion. The questions are sport oriented (e.g., which half is the game at, who scored last, which team did the athlete played last time). The Standardised Assessment of Concussion include orientation questions, as well as immediate memory test and concentration tests. The orientation questions are related to where they are in time: the year, the month, the time, the date, and the day. For the immediate memory test, the athlete will need to repeat 5 words previously said by the examinator in any order and will have three trials to do so. For the concentration tests, there are two components: repeating a list of digits backward to the examinator and telling the twelve months in reverse order to the examinator. The last cognitive test is the delayed recall test. Five minutes after completing the immediate memory test, the athlete will have to recall the five words they had to repeat before to the examinator. Even though this battery of tests is helpful during the sideline assessment, it does not replace a complete neuropsychological evaluation by a neuropsychologist.[5]

Balance is also assessed with the SCAT-5 because a concussion can cause some gait unsteadiness. The first test has three trials and is called the Modified Balance Error Scoring System (mBESS) test. The athlete will have to stay motionless with their eyes close during 20 seconds for each trial. The first trial is with a double leg stance, the second one is a single leg stance and the last one is a tandem stance. The evaluator will count any errors made during those 20 seconds. Errors can be if the athlete opens their eyes, removes their hands from their hips, step, stumble or fall for example. The second test to assess balance is the Tandem Gait test. The athlete needs to follow a line while touching their heel to their toes at each new step. The athlete fails if they step off the line, the toes and heel do not touch or the athlete grabs or touches and object or the examinator.[5]

The military uses a derivative of the Standardized Assessment of Concussion and the Brief Traumatic Brain Injury Screen, called the MACE, which stands for Military Acute Concussion Evaluation. The MACE-2 is composed of symptoms evaluation, cognition testing, neurological exam, including a balance assessment, and vestibular/ocular-motor screening.[76] The cognitive results are between 0 to 30, the neurological examination's results can be categorized either green or red and the symptoms either A or B. For example, if someone has a normal cognitive assessment with a score of 28 and a normal neurological examination, but abnormal symptoms, there result would be 28 Green Bravo.[22] The symptoms section is similar to the SCAT-5, with the most common symptoms listed (headache, dizziness, memory problems, etc.). The cognition exam also includes the Maddock questions and the Standardized Assessment of Concussion, with questions that are more general and not specific to sports (e.g., “Is there a period of time you cannot account for?”, “What is the first thing you remember after the event?”).[76]

The neurological exam consists of 8 different assessments. The first one, Speech Fluency, is to assess if speech is fluid without unnatural breaks. The second one is Word Finding. It is to assess any difficulties with word findings such as naming an object. The third one is Grip Strength, making sure it is strong and equal on both sides. The assessment test if the Pronator Drift test where the patient will stand with their eyes close, and arms extended in front of them. Any arm or palm drift is considered abnormal. The next two tests are balanced tests: Single leg stance and Tandem Gait. The two last tests are assessing optic nerves: pupil response to light and eye tracking

Vision portion of assessment. Even though the SCAT-5 helps to assess different components after a concussion, this assessment does not look at vision. However, vision has been showed to be impacted after a concussion, even weeks after the initial injury. Vision is composed of two important systems: the vestibulo-ocular system, which is the visual stability during head movement and the vestibulospinal system, which is for postural control.[36] Both of those systems can delay someone’s recovery if not treated correctly.[30] Easily accessible vision tests for athletes are the King Devick test and the VOMS Assessment test. The King Devick Test is a test that looks at impaired eye movements and saccades and is based on the time to perform a rapid naming of a series of single digit numbers from left to right. The athlete that does the King Devick Test needs to read aloud the series of single digit numbers as quickly as possible without making any mistakes.[81] The King Devick test is good to assess saccades, but this test does not look at smooth pursuit, convergence nor accommodation.[36] The VOMS Assessment looks at the basic visual functions: saccades, pursuits, accommodation, and vergence.[36] The VOMS assess vestibular and ocular impairment by provoking concussion symptoms. The screening assessment is composed of five tests assessing five different components: 1) smooth pursuit, 2) horizontal and vertical saccades, 3) convergence, 4) horizontal vestibular ocular reflex and 5) visual motion sensitivity.[36] VOMS have a high internal validity and a high sensitivity to diagnose a sport-related concussion if they are used in a comprehensive approach that also includes the Sport Concussion Assessment tool, a clinical examination, neuro-cognitive testing and balance assessment components.[36] VOMS can be used as a screening tool with the other tools used during the assessment. VOMS are primarily a symptom-based test and are not intended to be used as a comprehensive measure of vestibular or ocular motor impairments. VOMS are designed to elicit symptoms to help with referral and rehabilitation.[36] For the US military, VOMS Assessment is a part of the MACE-2, unless the patient is overtly symptomatic. If in theatre, the health care providers will assess the VOMS as well as look for any red or yellow flags for vision: diplopia, pupillary abnormalities, eyestrain, persistent visual disturbance, and others.[22] However, they are not assessing visual performance deficits.

Vision related to increased number of concussions

In a study by Harpham et al, 2013, the researchers hypothesized that the visual sensory performances of an athlete may not only be linked to sport performances, but also collision anticipation. Evaluating the visual and sensory performances could help find at-risk athletes and could help intervene to decrease the athlete's risks of injury. For this study, the researchers recruited 38 Division I football players and added a Head Impact Telemetry System to collect data on helmets' linear and rotational acceleration. The participants also had to perform the visual sensory testing on the Nike SPARQ Sensory Station, the Stroop, Simple Reaction Time, and the Procedural Reaction Time tests before the start of their season. For statistical analysis, the researchers used a Pearson product-moment correlation coefficient between reaction time and reaction time measured by the Nike SPARQ Sensory Station. They also did random intercepts general mixed linear models and Chi square analyses were performed to assess the association between visual and sensory performance and a categorized variable of impact severity based on the acceleration measures. In the end, a significant association between the severity of the head trauma and the performance on certain visual and sensory tasks was made, showing a strong association between the performances on the perception span, depth perception and go/no-go tests with the head impact severity.[7] Athletes who performed worse sustained more severe head impacts. For example, high performers in the Depth Perception test had a 47% frequency of recorded severe head impacts compared to 56% in low performers. High performers in the

Perception Span had a 31% frequency compared to 72% for the low performers.[7] Both the perception span and depth perception tests are complex and require a higher level of attentional focus to execute the tests at maximal speed with as little errors as possible. Those complex tests require a higher processing demand which is why those scores might be worse in concussed participants. Players that had worse overall scores were found to have an increased likelihood of sustaining severe head impact.[7,35] It is possible that these players were not able to properly assess and interpret environmental cues and anticipate the actions of their opponents, which cause the players to not create the appropriate motor response. The perception span task seems important because athletes with lower performance had twice as many severe head impact compared to athletes with better performances.[7,35] In another study, researchers stated that vision plays a preparatory role for collision avoidance, saying that collision avoidance behaviour is based both on the central visual field and the rapid switching behaviors to have a better survey of the visual scene. They also hypothesized that there should be a link between oculomotor performance variables and injury-related outcomes. If an athlete has a reduced accuracy in oculomotor performance, the athlete will have an increased number of head impacts. The researchers found that a less efficient performance on certain oculomotor tests was related to a higher number of head impacts.[82] The tests were assessing prosaccade, self-paced saccade and smooth pursuit. The researchers also wanted to look at the g force exposure and chose three cut-offs g force values based on the literature: 20, 50 and 100g force. Self-paced saccade velocity ($p=.02$) as well as the variability of smooth pursuit gaze velocity ($p=.012$) were positively associated with total collisions when the cut-off on their helmet was a 50g force.[82] An increase variability of prosaccade latency, a reduced performance with self-paced saccade and an increased variability of gaze velocity during smooth pursuit are all related to an increased risk of head impacts.[82]

An exploratory study in 2015 found that there was a decreased incidence of concussion during the season among football players where vision training was added to their preseason training.[83] The main goal was to find a way to decrease the risk of concussions that is easily adoptable by the coaching and medical teams. The researchers hypothesized that preseason vision training would significantly decrease the risk of both practice and competition concussion incidence in football. For this study, the researchers added a vision training among a university's football team and continued it for four years. The vision training was conducted during two weeks of the preseason camp. The vision training consisted of a light board training, the Nike strobe glasses, and tracking drills. During the preseason, the intensity and difficulty of the vision training would increase over time. During the football season, athletes had to perform only the Dynavision once a week for about 10 minutes. The researchers monitored the incidence of concussion during the four years and compared them to the previous four consecutive seasons. The concussion rates were compared between vision training and referent untrained conditions by using a Chi-square test with a Yates correction. They also did a post-hoc analysis and found that peripheral vision had improved over time. Players who followed the vision training had 1.4 concussions per 100 players whereas players who did not receive the vision training had 9.2 concussions per 100 players ($p<.001$). The researchers suggested that an increased awareness of the field due to vision training could help in anticipating concussion-causing injuries.[83]

In conclusion, this literary review was a general overview of concussions and vision in both athletes and service members. We talked about mild traumatic brain injuries, the deficits due to this injury and the potential long term consequences, as well as the importance of assessing and knowing about concussions. We learned about vision, visual sensory performance, and the different domains of vision. Visual sensory performance outcomes deficits were present after concussions in some studies and the consequences of visual deficits were also explained. The next section is composed of our study on visual sensory performance outcomes deficits in US Special Operations Forces combat Soldiers. We looked at mild traumatic brain injury history as well as lifetime incidence and recency. We explained our results and what they could mean for the future in concussion rehabilitation for the military, but also for athletes.

Chapter II
Manuscript

Assessing Visual Sensory Performance Outcomes of Special Operations Forces Combat Soldiers With or Without a Mild Traumatic Brain Injury

Abstract

Special Operations Forces (SOF) combat Soldiers endure various occupational exposures including blunt and blast head trauma. These exposures may result in occupational injuries, which can negatively affect human performance. Vision contributes to human performance, and existing data support two premises: 1) concussions adversely affect vision, and 2) visual deficits are associated with increased head impact frequency and severity, and decreased impact anticipation. Thus, this study's objective was to compare visual sensory performance outcomes in SOF combat Soldiers with and without concussion history.

Methods: This cross-sectional study consented 376 male Special Operations Forces combat Soldiers (age=32.7±3.6 years) self-reporting their lifetime concussion history (No history=159; History=208), lifetime incidence (0=159; 1-2=80; 3+=124) and recency (past month=24, past year=32; year+=134). The Senaptec Sensory Station (SSS) was then used to collect visual sensory performance in a clinical research center. The SSS is a computer-based unified testing platform (touchscreen tablet, responsive large screen, smartphone interface, and stereoscopic glasses) that evaluates ten different vision domains: 1) Reaction Time, 2) Eye-Hand Coordination, 3) Go/No-Go, 4) Visual Clarity, 5) Near Far Quickness, 6) Contrast Sensitivity, 7) Depth Perception, 8) Perception Span, 9) Multiple Object Tracking, and 10) Target Capture. Separate Wilcoxon rank-sum analyses compared our outcomes between concussion history groups, Kruskal-Wallis test was used for the incidence and recency due to data non-normality. Analyses were performed using SAS 9.4.

Results: For the mTBI history, the average Reaction Time significantly differed (Z=-3.28; P=.001) in Soldiers with a history of mTBIs (median = 329.0ms; IQR = 41.0) compared to those without a history of mTBIs (median = 318.50ms; IQR = 36.0). As for mTBI incidence, average Reaction Time, we observed a significant difference between SOF combat Soldiers who never sustained a mTBI (median = 318.5ms, IQR = 36.0) and those who sustained 1or 2 mTBIs (329.0ms, IQR = 30.0) and 3 or more mTBIs (median = 334.0ms, IQR = 45.0) (Z= 2.75, *P* = .02

and Z = 2.80, *P* = .01 respectively). As for peripheral Eye-Hand Coordination, we observed a significant difference between combat Soldiers who sustained 1 or 2 mTBIs (median = 649.68ms, IQR = 114.6) and those who sustained 3 or more mTBIs (median = 693.11ms, IQR = 130.95) (Z = -2.49, *P* = .034). For the NFQ reaction times to near targets [$\chi^2(2) = 18.99$, $P <$ .0001] were significantly different between combat Soldiers who never sustained a mTBI (median = 132.73ms, IQR = 1,005.61) compared to combat soldiers who sustained 3 or more mTBIs (median = 92.92ms, IQR = 842.82) (Z= -2.68, *P* = .02). Lastly, recency had an impact on Go/No-Go [$\chi^2(2) = 8.32$, *P* = .02]. Soldiers who sustained a mTBI within the past month had worse scores (median = 9.0 hits, IQR = 7.5) than those who sustained a mTBI more than a year ago (median = 12.0, IQR = 14.0) (Z=-2.55, *P* = .03). In mTBI recency, we also observed significant differences in NFQ for both average reaction time to near target [$\chi^2(2) = 9.13$, *P* = .01] and far target [$\chi^2(2) = 15.35$, *P* = .0005]. NFQ Reaction time to near target was worse in warfighters who sustained a mTBI within the past month (median = 983.6ms, IQR = 1,300.9) compared to those who sustained a mTBI over a year ago (median = 97.0ms, IQR = 908.1) (Z= 2.92, *P* = .01). NFQ Reaction time to far target was worse in Soldiers who had a mTBI within the past month (median = 479.6ms, IQR = 859.5) compared to those who self-reported a mTBI in the past year (median = 78.04ms, IQR = 344.73) and over a year (median = 73.4ms, IQR = 79.5) (Z = 3.23, *P* = .004 and Z = 3.79, *P* = .0004 respectively).

Conclusion: We observed decreased visual sensory performance outcomes in SOF combat Soldiers with a mild traumatic brain injury history. Soldiers' ability to react quickly to a threat (Reaction Time), to inhibit motion to distracting stimuli (Go/No-Go), and to change focus from near to far threats (Near-Far Quickness) may all be affected after a mTBI. Taken together, these findings may indicate diminished occupational performance and add to the recent literature intersecting mTBI history with human performance declines. These data may offer insights into rehabilitation and training mechanisms aimed at optimizing Soldiers for their occupational responsibilities following injury.

Competing interests

Dr. Mihalik is the Chief Science Officer and holds an equity interest in Senaptec Inc., the company that sells the Senaptec Sensory Station which was used to collect data for this study.

Introduction

With 82.3% of all the traumatic brain injuries (TBI) sustained since 2000 being mild traumatic brain injuries, they are the most common traumatic injury in the US military.[9–11] In 2020 only, 16,551 traumatic brain injuries were recorded, including 13,755 mild traumatic brain injuries.[10] This health issue has raised concerns from researchers, clinicians, military organizations, and Soldiers over the past few years. The incidence of mild traumatic brain injuries is higher due to the increased deployment of US Soldiers. Since 2001, around 1.3 million US military members have been deployed to Afghanistan and Iraq.[12–14] However, it is sometimes harder to diagnose a mild traumatic brain injury in the military to the potential of multiple injuries, sometimes life-threatening, and the situation the service members are in (i.e., In-theater, safe space, mission).[15,22,75,76]

After a diagnostic, one of the main indicators to return to duty is the resolution of symptoms.[9,15,22] Even though symptoms are important, vision should also be a key element to assess before full return to duty. In studies assessing visual deficits and mild traumatic injuries, significant visual deficits have been found in people who sustained a mild traumatic brain injury.[67,75,84] Athletes that sustained a sport-related concussion had impaired saccadic functions, convergence abnormalities, decreased visual accuracy and found it hard to keep visual attention.[30] In the military, personnel who sustained a mild traumatic brain injury had worse convergence insufficiency, pursuit and saccadic eye movements than personnel with no history of mild traumatic brain injuries.[84] After a concussion, the eyes ability to work together, in terms of depth perception and dynamic visual acuity, might be weakened.[30,68,84] However, researchers observed that some athletes who had no more concussion symptoms and were cleared to return to play still had visual deficits.[7,16] Those deficits can also go unrecognized in service members who sustained a mild traumatic brain injury and even last years later. [67] A significant association between the severity of the head trauma and the performance on certain visual and sensory tasks was made, showing a strong association between the performances on the perception span, depth perception, target capture and go/no-go tests with the head impact severity.[7] Athletes who performed worse sustained more severe head impacts.

A decrease in visual perception can increase the risk of injury and decrease one's performance.[30] Anticipation and visual performance may influence the severity as well as the frequency of head impact.[2] In the military, vision after a mild traumatic brain injury is assessed using the VOMS

Assessment test.[15,22,75] However, VOMS are primarily a symptom-based test and are not intended to be used as a comprehensive measure of vestibular or ocular motor impairments. The VOMS is designed to elicit symptoms to help with referral and rehabilitation.[36]

Therefore, the purpose of this study was to compare visual sensory performance outcomes in Special Operations Forces Combat Soldier with or without a history of mild traumatic brain injury. The first objective was to use the Senaptec Sensory Station to assess the visual and sensory performance scores in Special Operations Forces Combat Soldiers after they sustained a mild traumatic brain injury compared to those who did not sustain a mild traumatic brain injury. Our hypothesis was that SOF Combat Soldiers with a concussion history would score worse in the visual sensory performance assessment. Our second objective was to compare the visual sensory performance scores between three groups: no concussion, between 1 and 2 concussions, 3+ concussions. Our second hypothesis was that poorer performances on the Senaptec Sensory Station would be associated with a higher number of mild traumatic history. Our third objective was to compare visual sensory performance scores between combat Soldiers who sustained a mild traumatic brain injury within the past month, the past year and with Soldiers who sustained one over a year ago. Our hypothesis was that there will be no difference between the three groups.

Methods

Participants

Each Special Operations Force Combat Soldier completed verbal consent following procedures approved by the Office of Human Research Ethics at the University of North Carolina at Chapel Hill. We used a cross-sectional study design. Our final study sample included 376 male Special Operations Forces combat Soldiers (mean age = 32.7 ± 3.6 years) from 2011 to 2021. Exclusion criteria included: (1) vision impairment (permanent vision loss, strabismus, color blindness, and abnormal vestibular function that would impede their performance, (2) retired SOF combat Soldier, and (3) any known neurocognitive deficits prior to concussion injury.

Instrumentation: Senaptec Sensory Station

The Senaptec Sensory Station is a computer-based system programmed to evaluate ten different visual and sensory performance. The sensory station includes a responsive large screen, a height-adjustable Samsung touch-screen tablet, a Motorola touch-screen smart phone and stereoscopic glasses.

The following are the tests that were performed by the participants.

1. Reaction Time – Inhibitory control

   Standing at arm's length of the screen, two circles with smaller circle inside appeared on each side of the screen. The participant had to keep their index fingers on the smaller circles. After 2, 3 or 4 seconds, one of the inner circles turned red, and the participant had to remove their index finger as rapidly as possible while keeping the other index in place. The task was completed seven times. Reaction times were calculated for both hands together and separately.

2. Eye-Hand Coordination – Proprioception

   Participants returned at arm's length of the 50-inch screen. The screen showed an 8x10 matrix of 80 circles, where one was illuminated green. The participants were instructed to touch the green circle as quickly as possible. As soon as one green circle was touched, another one appeared green. The test ended after a series of 80 pseudorandomized circles. The participants saw the green circles as random, however, the circles were controlled to avoid any clusters or recognizable sequences.

3. Go/No-Go – Inhibitory Control

   Participants stayed at arm's length of the screen, which displayed an 8x10 matrix of circles. The circles were either green or red. The participants had to touch the green circles as quickly as possible and avoided the red circles. Each circle, whatever the color, was illuminated for 500ms before a new circle was illuminated. The outcome was the amount of correct green circles hit minus the number of red circles selected, with 25% credit given to any green circles that were hit late. To avoid any clusters or recognizable sequences, the same pseudo randomization as the Hand-Eye Coordination test was used.

4. Visual Clarity – Static visual acuity

   Participant stepped on the 10 feet line, facing the screen. The test was done 3 times. The test administrator occluded one eye using an eye occluder for the first try, then the other eye for the second try, and, finally, none for the third try. A

Landolt ring (circular ring with a gap) appeared on the screen. The gap was randomly either at the top, bottom, left or right. The participant swiped on the phone towards the gap of the ring. The Landolt ring decreased in size (0.1 log units) until size is -0.3 or until the participant made a mistake. The goal was to determine the smallest size where the participant could still correctly identify the gap in the ring.

5. Near-Far Quickness – Accommodative vergence facility

    The Near-Far Quickness test used the results from the Visual Acuity test. The better score, the smaller the Landolt ring appeared on the screen of the tablet. Participant were still 10 feet away from the screen, this time holding the phone in front of them. Landolt rings appeared alternatively on the phone and the tablet screen. The participant needed to swipe on the phone towards the gap, alternating whether they were looking at the tablet or the phone. The test ended after 30 seconds.

6. Contrast Sensitivity – Perception ability

    While still being 10 feet away from the screen, the participant kept using the phone as a response device. On the tablet's screen, four circles appeared in a diamond configuration. One of those circles had a set of circles that vary in brightness. The participant swiped on the phone towards the direction of the circle with the circle pattern. After every correct response, the circles became fainter, making it harder for the participant. Reversal points were used until the faintest level where the participant could still accurately identify the circle pattern was found. Contrast sensitivity was assessed at 2 spatial frequencies: 6 cycles per degree and 18 cycles per degree.

7. Depth Perception – Stereopsis

    The test administrator gave the participant the stereoscopic glasses. The participant stayed 10 feet from the screen and kept using the Motorola phone. Depth perception was assessed by doing the test three times: one facing sideways to look over their right shoulder, one looking over their left shoulder, and then one facing the tablet, looking straight ahead. On the screen, four circles appeared in a diamond configuration. One ring appeared to be floating compared to the others.

The participant had to swipe on the phone in the direction of the floating circle, which became harder to identify. Again, the test ended when the faintest difference identified was determined.

8. Perception Span – Central visual recognition accuracy

    The participant stood at arm's length in front of the tablet and interacted with the tablet. The participant needed to look at the center of a grid pattern. For 100ms, a pattern of dots flashed (they were pseudorandomized so no shape could be recognized) in the grid. The participant had to recreate the pattern shown previously by pressing on the dots necessary. The pattern became larger and more difficult if the participant had at least 75% accuracy. The levels could go from six circles with 2 or 3 dots highlighted, to thirty circles with 7 to 10 dots flashing. The test ended after two failed attempts.

9. Multiple Object Tracking – Attention performance

    The participant stayed at arm's length of the screen. Between 2 to 8 pairs of dots appeared on the screen, depending on the participant's performance, where the participant was asked to remember the tracked dot. The dot that would be tracked became red for one second at the start of each trial. Each pair of dots rotated independently in different directions for five seconds. When the dots were done rotating, the participant needed to select the dots that were previously red. A total of 10 trials were done, with the number of pairs and the speed of rotation varying during the assessment. If the participant made more incorrect answers, the rotations became slower, and the number of pairs decreased.

10. Target Capture – Dynamic Visual Acuity

    Participants returned on the 10 feet line, away from the 50-inch screen raised to eye level, using the cell phone to interact with the visual stimuli. The participant was asked to focus on the center of the screen, and a ring briefly appeared in one of the corners of the screen. Participant was instructed to find the ring and swipe their finger in the direction of the gap on the ring. With each correct answer, the time that the ring appeared on the screen was reduced.

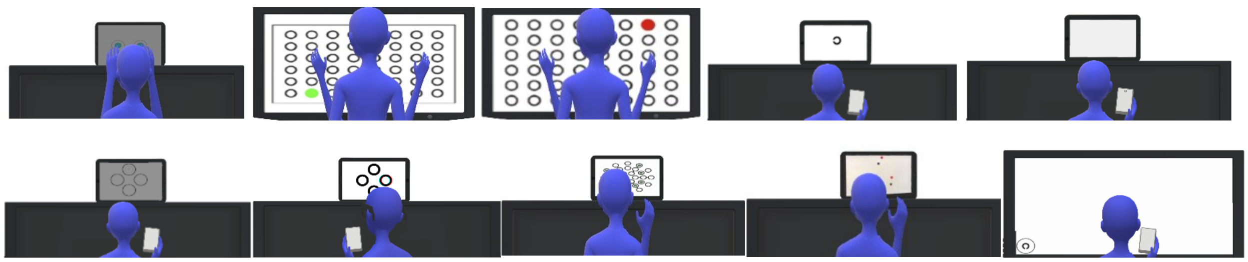

Figure 5. Visual Sensory Performance Tests (From left to right: Reaction Time, Eye-Hand Coordination, Go/No-Go, Visual Clarity, Near-Far Quickness, Contrast Sensitivity, Depth Perception, Perception Span, Multiple Object Tracking, Target Capture)

Procedures

Soldiers completed a visual and sensory performance assessment using the Senaptec Sensory Station. Before the assessment started, participants completed a questionnaire relative to their year of birth, height, concussion history and vision exam history. Participants self-reported mild traumatic brain injury history as a dichotomized response: 159 SOF combat Soldiers self-reported no mild traumatic brain injury, and 208 SOF combat Soldiers self-reported a history of mild traumatic brain injury. We asked them to self-report lifetime mild traumatic brain injury incidence and mTBI recency. Before completing the Senaptec visual sensory performance tests, Soldiers answered a few questions on their lifetime history of mild traumatic brain injury: "Have you ever had a concussion in the past?", "How many concussions have you had?", and "When was the most recent one?".

After that, the participant stood on the 10 feet mark on the ground, facing the Senaptec Sensory Station's tablet. The test administrator gave the instructions for each test, as an example video was played to explain the test before it started. Each task was preceded by a practice round. Before the first task, the test administrator prepared the Motorola touch-screen smartphone connected to the tablet and the stereopsis glasses for the participant. The tasks were performed in the same order for each participant: 1) Visual Clarity, 2) Contrast Sensitivity, 3) Depth Perception, 4) Near-Far Quickness, 5) Perception Span, 6) Multiple Object Tracking, 7) Reaction Time, 8) Target Capture, 9) Eye-Hand Coordination, and 10) Go/No-Go.

Statistical Analysis

All data analysis was done using SAS 9.4. We tested for normality using four tests for each variable: Shapiro-Wilk, Kolmogorov-Smirnov, Cramer-von Mises, and Anderson-Darling. The *p*-value was always under .05, rejecting the null hypothesis, and accepting the alternative hypothesis that the distribution does not have a normal distribution. We used nonparametric tests to analyze our data. For the first objective, we used a Wilcoxon rank-sum analysis to compare the outcomes between the group with a history of mild traumatic brain injury and the group without history. The Wilcoxon rank-sum test, also known as the Mann Whitney U test, is used to compare two independent samples, using summed rank scores. For the second objective, we used the Kruskal-Wallis test, which is the nonparametric equivalent of the ANOVA test, to compare the groups with reported frequency of mild traumatic brain injury. The Kruskal-Wallis tests whether medians of three or more independent groups are significantly different. For significant findings, a pairwise two-sided multiple comparison analysis Dwass, Steel, Critchlow-Fligner method was applied. For the third objective, we used the Kruskal-Wallis test to compare mild traumatic brain injury recency. For significant findings, we used the Dwass, Steel, Critchlow-Fligner method. All statistical tests were 2-tailed with a set a priori α level at $p<.05$. All medians and interquartile ranges are in Appendix 1.

Results

Mild Traumatic Brain Injury History

The average reaction time for the dominant hand was significantly slower (Z= -3.76; P = .0002) in SOF combat Soldiers with mTBI history compared to those without mTBI history (see table 2). Similarly, the average reaction time for the non-dominant hand was significantly slower (Z= -2.40; P = .016) between SOF combat Soldiers with a history of mTBIs and without. The average reaction time is significantly slower (Z=-3.28; P=.001) in Soldiers with a history of mTBI compared to those without a history of mTBIs. The Eye Hand Coordination total times were statistically significantly faster (Z= 2.51; P = .012) in those with mTBI history compared to those without a mTBI history. The Go/No-Go total scores were significantly different (Z= -5.61; P<.0001) in those with mTBI history compared to those without mTBI history.

Table 2. Significant Differences in Visual Sensory Performance Outcomes presented as median (IQR) across the mTBI History group and the No mTBI History group.

Group Variables	Average Reaction Time dominant hand (ms)	Average Reaction Time non dominant (ms)	Average Reaction Time (ms)	Eye Hand Coordination Total Time (ms)	Go/No-Go Total Score
mTBI History					
Yes (n=159)	331.5 (43.0)*	327.0 (46.5)*	329.0 (41.0)*	47,352.0 (5,608)*	11.0 (12.0)*
No (n=208)	318.5 (36.0)	318.5 (41.0)	318.5 (36.0)	48,734.0 (5,941.0)	6.0 (9.0)

* Indicates significant difference between the groups.

Mild Traumatic Brain Injury Incidence

We observed significant differences in Reaction Time for the dominant hand ($\chi2(2)$ =14.68, P = .0006) and the average reaction time [$\chi2(2)$ =11.08, P = .004] (see table 3). For the reaction time of the dominant hand, we observed a significant difference between Soldiers who never sustained a mTBI and those who sustained 1 or 2 mTBIs as well as Soldiers who sustained 3 or more mTBIs (Z=3.17, P = .004 and Z=3.22, P = .004 respectively). We observed a significant difference in average reaction time between SOF combat Soldiers who never sustained a mTBI and those who sustained 1 or 2 mTBIs and 3 or more mTBIs (Z= 2.75, P = .02 and Z = 2.80, P = .01 respectively). SOF combat Soldiers with no history of mTBI had a faster average reaction time compared to the other groups. We observed a significant difference in the Eye Hand Coordination test for both the total time [$\chi2(2)$ = 8.58, P = .01] and the peripheral average reaction time [$\chi2(2)$ =7.28, P = .03]. The total time in combat Soldiers was significantly different between those who never sustained a mTBI and those who sustained 3 or more mTBIs (Z= -2.87, P = .01). As for the peripheral average reaction time, we observed a significant difference between combat Soldiers who sustained 1 or 2 mTBIs and those who sustained 3 or more mTBIs (Z = -2.49, P = .034). The Go/No-Go total scores were significantly different [$\chi2(2)$ = 42.76, P <.0001]. Soldiers who sustained 3 or more mTBIs in their lifetime scored better than those who never had a mTBI or between 1 and 2 mTBIs (Z = 6.41, P <.0001 and Z = -3.50, P = .001 respectively). Soldiers who sustained between 1 and 2 mTBIs also scored better than those who never sustained a mTBI (Z = 2.44, P = .04). There was a significant difference in Visual Clarity observed across mTBIs incidence (0, 1 to 2, 3+ mTBI) [$\chi2(2)$ = 7.41, P = .02]. These differences were mostly caused by SOF combat Soldiers who sustained 3 or more mTBIs compared to combat Soldiers who never sustained a mTBI. A significant difference was also found in the Near Far Quickness average reaction time to near target [$\chi2(2)$ = 18.99, P < .0001]. The most significant difference was between combat Soldiers who sustained 1 or 2 mTBIs in their lifetime compared to those who sustained 3 or more mTBIs (Z= 4.16, P < .0001). Moreover, we observed a significant difference between combat Soldiers who never sustained a mTBI compared to combat Soldiers who sustained one or two mTBIs as well as those who sustained 3 or more mTBIs (Z= 2.38, P = .046 and Z= -2.68, P = .02 respectively). There also was a main effect of mTBI lifetime incidence on Near Far Quickness average reaction time to far targets [$\chi2(2)$ = 13.96, P = .0009]. The average reaction time was slower in combat Soldiers who sustained one or two mTBIs compared to those who sustained 3 or more mTBIs (Z= 3.56, P = .001). Near Far Quickness average reaction time to far was also slower in combat Soldiers who never sustained a mTBI compared to SOF combat Soldiers who self-reported 3 or more mTBIs (Z= -2.35, P= .0498).

Table 3a. Significant Differences in Visual Sensory Performance Outcomes presented as median (IQR) across the mTBI Lifetime Incidence groups (0 mTBI, 1-2 mTBI, 3 or more mTBIs)

Group Variables	Reaction Time Dominant hand (ms)	Average Reaction Time (ms)	Eye Hand Coordination Total Time (ms)	Eye Hand Coordination Peripheral Average Reaction Time (ms)
Lifetime Incidence				
0 (n=159)	318.5 (36.0)[a,b]	318.5 (36.0)[c,d]	48,734.0 (5,941.0)[e]	653.09 (135.5)
1-2 (n= 80)	332.0 (34.0)[a]	329.0 (30.0)[c]	48,033.0 (5,023.5)	649.68 (114.6)[f]
3+ (n= 124)	330.0 (47.0)[b]	334.0 (45.0)[d]	46,520.0 (5,780.0)[e]	693.11 (130.95)[f]

[a] Average Reaction Time dominant hand significantly faster in combat Soldiers with 0 mTBI versus 1-2 mTBI.
[b] Average Reaction Time dominant hand significantly faster in combat Soldiers with 0 mTBI versus 3+ mTBI.
[c] Average Reaction Time significantly faster combat Soldiers with 0 mTBI versus 1-2 mTBI.
[d] Average Reaction Time significantly faster combat Soldiers with 0 mTBI versus 3+ mTBI.
[e]Eye Hand Coordination total time significantly slower in combat Soldiers with 0 mTBI versus 3+ mTBI.
[f] Eye Hand Coordination peripheral average reaction time significantly faster in combat Soldiers with 1-2 mTBI versus 3+ mTBI.

Table 3b. Significant Differences in Visual Sensory Performance Outcomes presented as median (IQR) across the mTBI Lifetime Incidence groups (0 mTBI, 1-2 mTBI, 3 or more mTBIs)

Group Variables	Go/No-Go Total Score	Visual Clarity	Near Far Quickness Average Reaction Time to Near (ms)	Near Far Quickness Average Reaction Time to Far (ms)
0 (n=159)	6.0 (9.0)[g,h]	-0.194 (0.124)[j]	132.73 (1,005.61)[k]	81.42 (638.63)[m]
1-2 (n= 80)	7.0 (9.5)[g,i]	-0.194 (0.124)	922.56 (1,134.77)[l]	119.6 (778.0)[n]
3+ (n= 124)	12.0 (13.0)[h,i]	-0.194 (0.124)[j]	92.92 (842.82)[k,l]	77.46 (122.71)[m,n]

[g] Go/No-Go significantly lower in combat Soldiers with 0 mTBI versus 1-2 mTBI.
[h] Go/No-Go significantly lower in combat Soldiers with 0 mTBI versus 3+ mTBI.
[i] Go/No-Go significantly lower in combat Soldiers with 1-2 mTBI versus 3+ mTBI.
[j] Visual Clarity statistically significant different in combat Soldiers with 0 mTBI versus 3+ mTBI.
[k] Near Far Quickness to near significantly slower in combat Soldiers with 0 mTBI versus 3+ mTBI.
[l] Near Far Quickness to near significantly slower in combat Soldiers with 1-2 mTBI versus 3+ mTBI.
[m] Near Far Quickness to far significantly slower in combat Soldiers with 0 mTBI versus 3+ mTBI.
[n] Near Far Quickness to far significantly slower in combat Soldiers with 1-2 mTBI versus 3+ mTBI.

Mild Traumatic Brain Injury Recency

Mild traumatic brain injury recency had an impact on Go/No-Go [$\chi2(2)$ =8.32, P = .02] (see table 4). Soldiers who sustained a mTBI within the past month had worse scores than those who sustained a mTBI more than a year ago (Z=-2.55, P = .03). As for Near Far Quickness, recency had a main effect on both average reaction time to near target [$\chi2(2)$ =9.13, P = .01] and far target [$\chi2(2)$ =15.35, P = .0005]. Reaction time to near target was worse in warfighters who sustained a mTBI within the past month compared to those who sustained a mTBI over a year ago (Z= 2.92, P = .01). Reaction time to far target was worse in Soldiers who had a mTBI within the past month compared to those who self-reported a mTBI in the past year and over a year (Z = 3.23, P = .004 and Z = 3.79, P = .0004 respectively). A main effect of mTBI recency on Contrast Sensitivity at 6 cycles per degree and 18 cycles per degree was also observed [$\chi2(2)$ =8.05, P = .02 and $\chi2(2)$ =11.19, P = .004]. Specifically, contrast sensitivity at 6 cycles per degree was significantly different in Soldiers who had a mTBI in the past year compared to those who sustained a mTBI over a year ago (Z = -2.86, P = .01). Finally, we observed a significant difference at 18 cycles per degree between Soldiers who sustained a mTBI in the past year compared to those who sustained a mTBI in the past month and over a year ago (Z= 2.50, P = .033 and Z = -3.27, P = .0031).

Table 4. Significant Differences in Visual Sensory Performance Outcomes presented as median (IQR) across the mTBI Recency groups (Past month, Past year, Over a year ago)

Group Variables	Go/No-Go Total Score	Near Far Quickness Average Reaction Time to Near (ms)	Near Far Quickness Average Reaction Time to Far (ms)	Contrast Sensitivity (6 cycles/degree)	Contrast Sensitivity (18 cycles/degree)
mTBI Recency					
Past month (n=24)	9.0 (7.5)[a]	983.6 (1,300.9)[b]	479.6 (859.5)[c,d]	2.2 (0.3)	1.6 (0.3)[f]
Past year (n=32)	11.0 (10.0)	113.59 (938.44)	78.04 (344.73)[c]	2.0 (0.3)[e]	1.4 (0.2)[f,g]
Year+ (n=134)	12.0 (14.0)[a]	97.0 (908.06)[b]	73.43 (79.53)[d]	2.2 (0.2)[e]	1.6 (0.3)[g]

[a] Go/No-Go total score significantly lower in combat Soldiers with mTBI within past month versus year+.
[b] Near Far Quickness to near significantly slower in combat Soldiers with mTBI within past month versus year +.
[c] Near Far Quickness to far significantly slower in combat Soldiers with mTBI within past month versus past year.
[d] Near Far Quickness to far significantly slower in combat Soldiers with mTBI within past month versus year+.
[e] Contrast Sensitivity at 6 cycles per degree significantly worse in combat Soldiers with mTBI within past year versus year +.
[f] Contrast Sensitivity at 18 cycles per degree significantly better in combat Soldiers with mTBI within past month versus past year.
[g] Contrast Sensitivity significantly worse in combat Soldiers with mTBI within past year versus year +.

Discussion

The purpose of this study was to compare visual sensory performance outcomes in Special Operations Forces combat Soldiers with and without mild traumatic brain injuries. The Senaptec Sensory Station was used to differentiate between groups by evaluating the following variables: Reaction Time, Eye Hand Coordination, Go/No-Go, Visual Clarity, Near Far Quickness, Contrast Sensitivity, Depth Perception, Perception Span, Multiple Object Tracking, and Target Capture.

While there is evidence that visual sensory performance outcomes are affected by a history of mild traumatic brain injury, [29,59,67,70] we observed Special Operations Forces combat Soldiers with a history of mTBIs performed better than those without history in Eye Hand Coordination test and the Go/No-Go tests, which is similar to previous studies. For example, Poltavski et al. noted athletes with a concussion history had a faster Eye Hand Coordination as well as better results in the Go/No-Go compared to their control group.[85] In our study, the better performances by the Soldiers with a history of mTBIs compared to the Soldiers without a history of mTBI could potentially be explained by differences in groups mean ages as well as cognitive differences such as education levels or Attention Deficit Hyperactivity Disorder (ADHD) that were not reported.[86] We observed significant differences between ages within groups (see appendix 2). In the concussion history and lifetime mTBI incidence groups, we observed that the group with the most concussions and with a concussion history were statistically significantly older than the other groups. With about a 2-year difference between the groups, the gap may not seem clinically significant. However, an extra two years could mean more time in the military and working on their skillset. The older groups could have a better reaction time, coordination, and inhibition due to more practice time compared to the younger groups. Moreover, the older group could have taken more educational courses, whether at school or in the military. It has been shown that people with higher education levels and without ADHD performed better on cognitive tests compared to people with lower education levels or with ADHD.[86] We also did not control for concussion treatment in the group with a history of mTBI. Treatments could help reduce the deficits caused by a mTBI.

For lifetime incidence of mild traumatic brain injury, in our study, general reaction time was worse in Soldiers who had a history of mTBI compared to those who don't have a history, which is consistent with the current literature on deficits after a mild traumatic brain injury.[87] For example, Womack et al. (2017) observed that an increased peripheral vision reaction time significantly correlated with a lower mean diffusivity in the posterior corpus callosum, which is often affected by mTBIs.[88] The reduction in mean diffusivity due to decreased white matter integrity could be associated with a cytotoxic edema, which has been seen in acute neuronal damages. The impairment of the corpus callosum, which connects the two hemispheres of the brain and ensures good communication, could be the cause of worse peripheral vision reaction time.[88] Moreover, Special Operations Forces combat Soldiers who sustained either one or two mTBIs in their lifetime had a better peripheral average reaction time when completing the Eye Hand Coordination test compared to combat Soldiers who self reported three or more mTBIs. In another study on long term effect of mild traumatic brain injuries in the military, they observed a decrease in the visual field, which could impact peripheral vision and the time to react to a stimulus on the periphery.[73] In that study, they did not ask for lifetime incidence, however, they observed that mTBI was associated with significantly greater thinning of the retinal nerve fiber layer over time in veterans. In our study, we observed that our group with 3 or more mTBIs in the past had worse Eye Hand Coordination peripheral average reaction time. However, recency did not seem to affect Eye Hand Coordination peripheral average reaction time, which is different from the study that observed greater thinning of the retinal nerve fiber layer over time.

It would be interesting to see if a slower peripheral average reaction time is correlated to a higher number of mTBIs.[73]

As for recency, we observed significant differences between Soldiers who sustained a mTBI in the past month compared to those who sustained one over a year ago. Outcomes for the Near Far Quickness for both the near target and far targets were worse in warfighters who sustained their injury within the past month, which correlate with studies showing deficits in accommodation after a sport-related concussion.[30,68,84] Contrast sensitivity was worse in Soldiers who sustained a mTBI within the past year compared to past month or over a year ago. In Harpham et al. (2014), they observed visual deficits in athletes that had comparable baseline score. The athletes had deficits in Contrast Sensitivity and Near Far Quickness, similarly to what we observed in our study.[7]

Visual sensory performance is the ability to receive sensory information from the eyes and combine it with somatosensory and vestibular information, to then produce the appropriate response. Multiple brain connections are needed for visual sensory performance to happen: connections to the brainstem, the cerebellum, the cerebral cortex, the ocular system, and the postural muscles. However, a mTBI will injure the axons or affect neuronal integrity, which will cause alterations in cerebral metabolism, control of the cerebral blood flow, cerebrovascular reactivity, and neurovascular coupling.[18,89] Visual sensory performance deficits could be caused by those alterations in the brain, as well as the decreased mean diffusivity in the brain due to white matter integrity and because of an injury the peripheral vestibular apparatus and the brainstem nuclei or the central processing structures, which can results in the inability to properly process sensory inputs. [72,73] In a study where researches observed neural activity, they observed lower scores in the mTBI group compared to athletes without a history of concussion as well as changes in neural activity while performing Target Capture, Perception Span and Hand Reaction Time on the Nike SPARQ.[85] In another study on neural activity, they observed deficits in the magnocellular and parvocellular, neurons specialized in detecting aspects of movements, in a group with a history of concussion.[90] In other words, visual sensory performance deficits could be due to the impaired autonomic system, altered neural activity and white matter integrity.

Visual sensory performance deficits, even if present, could be statistically significant, without being clinically significant. When we look at our results and medians, some results that are statistically significant different may seem clinically insignificant. In a sport environment, a few milliseconds may not make a difference. However, in a theatre of operations, a few milliseconds can reduce human errors and catastrophic failures. A decrease of 11ms in average reaction time, for example, may affect a combat Soldier's operational effectiveness. Warfighters' reaction time and neuromuscular systems are already close to optimum levels and a slight decrease could negatively impact their mission.[91v]To show how close Soldiers are to their optimum levels, we found a study that looked at average reaction time in Division 1 hockey players. Those players had an average time of 347.55ms. Soldiers in our study had an average reaction time of 318.5ms with no concussion history and 329.0ms with a concussion history.[65] SOF combat Soldiers' average reaction times show how their neuromuscular systems are close to optimal. Most accidents during training and battle are due to impaired cognitive performance such as vigilance, reaction time, working memory and reasoning.[92]

Limitations

Even though this study had a large sample size, the differences in certain group sizes were important. More participants will help with group sizes as well as the differences in age between groups. Moreover, results of this study can only be generalized to male Special Operations Forces combat Soldiers since we didn't assess female soldiers or soldiers from different units or branches. Finally, it would be interesting to add level of education, learning disabilities as well as if their mTBI were cause by blunt forces or a blast and if combat Soldiers received treatment. Mild traumatic brain injuries caused by blast forces are still not well understood and could impact visual sensory performances differently than mTBIs caused by blunt forces only. Combat Soldiers receiving treatment after their injury could have better visual sensory performance outcomes than those who did not seek treatment or do not have a history of mild traumatic brain injuries.

Conclusion

We observed decreased visual sensory performance outcomes in SOF combat Soldiers with a mild traumatic brain injury history. Soldiers' ability to react quickly to a threat (Reaction Time), to inhibit motion to distracting stimuli (Go/No-Go) may all be affected after a mTBI, and to change focus from near to far threats (Near-Far Quickness). Taken together, these findings may indicate diminished occupational performance and add to the recent literature intersecting mTBI history with human performance declines. Visual sensory performance outcomes may be a good way to evaluate deficits and residual effects that could be missed with traditional evaluation. Visual sensory performance could help better assess concussions and soldiers' limitations. These data may offer insights into rehabilitation and training mechanisms aimed at optimizing Soldiers for their occupational responsibilities following injury.

Chapter III

Executive Summary

We originally planned to do this study with athletes from different sports. However, due to different challenges, we had to change the population we wanted to look at. Those challenges included the impact of the pandemic on the athletes' ability to play sports as well as the absence of sport-related concussions in athletes. We expected around 20 concussed players during the fall and winter semesters, but only three athletes were concussed. During that time, we also assessed Special Operations Forces Combat Soldiers and thought it would be interesting to look at visual sensory performance outcomes in this population.

Even though this study was done with Special Operations Forces Combat Soldiers, these findings could also be potentially applied to athletes. Both combat Soldiers and athletes are subject to blunt mild traumatic brain injuries, also known as sport-related concussions. We saw how athletes' visual sensory performance outcomes are better than the normal population due to repeated training, complex environments, and high stress situations. A lot of knowledge in the military is based off sport-related concussions due to the high demands in athletes and their differences from the general population, even soldiers perform better in some tests. Average reaction time in Division I hockey players was 347.55ms, whereas we observed a reaction time in SOF combat Soldiers with no concussion history of 318.5ms.

In this thesis, we were able to compare visual sensory performance outcomes in Special Operations Forces Combat Soldiers depending on their mild traumatic brain injury history, recency, and lifetime history. We observed different results that were statistically significant. In traditional concussion assessment, for example the SCAT-5, vision is not assessed. VOMS can sometimes be done but VOMS are positive if they recreate symptoms. Most times, visual sensory performance is not evaluated after a concussion or to clear to return to play. Assessing different domains of vision could help discover deficits not found normally. The main result was the difference in reaction time. Combat Soldiers who have a history of mild traumatic brain injury had slower reaction times. In lifetime history of mild traumatic brain injuries, peripheral vision was worse in Soldiers who had more than 3 mild traumatic brain injuries. Visual accommodation was also worse in warfighters if they sustained a mTBI within the past month.

Even though we observed worse outcomes in combat Soldiers with a history of concussions, it is also important to note that some results were worse in Soldiers who never sustained a mTBI in the past. Those worse outcomes could be due to learning disabilities or ADHD, which were not asked.[86] We also did not control for concussion treatment, which could influence the Soldier's visual sensory performance outcomes. Moreover, even though the literature found significant differences in sport-related concussions[29,30,66,68], the mechanism of injury isn't always the same for Soldiers. Another question to ask Soldiers before they complete the study would be the cause of the mild traumatic brain injury. It is important to differentiate between blunt forces, blast exposure or a mixture of both to be able to observe any difference in visual performances outcomes depending on the mechanism of injury.

As for recency and lifetime incidence, we did ask how many mild traumatic brain injuries Soldiers had and when was the most recent one. However, it would be interesting to see how much time elapsed between the previous concussion if they've had more than one. In a study with US Marines, researchers observed that a lifetime history of more that 3 mild traumatic brain injuries did not correlate with post concussive symptoms. However, they observed that if US Marines sustained 2 concussive events within 6 months, they had more post concussive symptoms compared to US Marines who sustained 2 mild traumatic brain injuries over 6 months apart.[93]

In conclusion, we observed decreased visual sensory performance outcomes in SOF combat Soldiers with a mild traumatic brain injury history which may indicate decreased occupational performance. In life-threatening situations, a slight decrease in reactions and responses to stimuli could be vital. These data may offer insights into the effects of mild traumatic brain injuries on visual sensory performance outcomes in Soldiers as well as in athletes. Visual sensory performance outcomes may be a good way to evaluate deficits and residual effects that could be missed with traditional evaluation such as the SCAT-5 and the MACE-2. Visual sensory performance could help better assess concussions as well as athletes and soldiers' limitations. These data may offer insights into rehabilitation and training mechanisms aimed at optimizing

Soldiers. Visual sensory performance outcomes could also be used to individualize and guide rehabilitation in athletes and soldiers alike.

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Appendix 1

Table 5. Visual Sensory Performance outcomes presented as median (IQR) across the 3 grouping variables of interest: mTBI History, Lifetime incidence, mTBI Recency

Group Variables	mTBI History		Lifetime Incidence			mTBI Recency		
	Yes (n=159)	*No (n=208)*	*0 (n=159)*	*1-2 (n= 80)*	*3+ (n= 124)*	*Past month (n=24)*	*Past year (n=32)*	*Year+ (n=134)*
Visual Clarity Right	-0.07 (0.22)	-0.07 (0.22)	-0.07 (0.22)	-0.07 (0.22)	-0.07 (0.22)	-0.07 (0.22)	-0.07 (0.10)	-0.07 (0.22)
Visual Clarity Left	-0.07 (0.22)	-0.07 (0.22)	-0.07 (0.22)	-0.07 (0.22)	-0.07 (0.22)	-0.07 (0.22)	-0.07 (0.22)	-0.07 (0.22)
Visual Clarity	-0.194 (0.124)	-0.194 (0.124)	-0.194 (0.124)*	-0.194 (0.124)	-0.194 (0.124)*	-0.194 (0.124)	-0.07 (0.124)	-0.194 (0.124)
Contrast Sensitivity (6 cycles/degree)	2.2 (0.2)	2.2 (0.3)	2.2 (0.3)	2.2 (0.3)	2.2 (0.2)	2.2 (0.3)	2.0 (0.3)*	2.2 (0.2)*
Contrast Sensitivity (18 cycles/degree)	1.6 (0.4)	1.6 (0.4)	1.6 (0.4)	1.6 (0.4)	1.6 (0.6)	1.6 (0.3)[l]	1.4 (0.2)[l, m]	1.6 (0.3)[m]
Depth Perception	52.0 (93.0)	52.0 (186.0)	52.0 (186.0)	62.0 (145.0)	52.0 (73.0)	46.5 (57.0)	52.0 (114.0)	62.0 (145.0)
Depth Perception Left	57.0 (145.0)	62.0 (209.0)	62.0 (209.0)	72.0 (176.0)	52.0 (145.0)	72.0 (165.5)	52.0 (73.0)	62.0 (186.0)
Depth Perception Right	52.0 (93.0)	52.0 (186.0)	52.0 (186.0)	62.0 (186.0)	46.5 (73.0)	52.0 (83.0)	41.0 (73.0)	62.0 (166.0)
Near Far Quickness Score	26.0 (8.0)	25.0 (7.0)	25.0 (7.0)	25.0 (8.0)	26.0 (8.0)	24.0 (7.5)	26.0 (13.0)	25.0 (7.0)
Near Far Quickness Average Reaction Time to Near (ms)	123.4 (1,011.3)	132.7 (1,005.6)	132.7 (1,005.6) [b]	922.6 (1,134.8)[a]	92.9 (842.8) [a, b]	983.6 (1,300.9)*	113.6 (938.4)	97.0 (908.1)*
Near Far Quickness Average Reaction Time to Far (ms)	90.0 (676.6)	81.4 (638.6)	81.4 (638.6) [d]	119.6 (778.0)[c]	77.5 (122.7) [c, d]	479.6 (859.5)[n, o]	78.0 (344.7)[n]	73.4 (79.5) [o]
Perception Span	46.0 (22.0)	41.0 (22.0)	41.0 (22.0)	47.0 (22.0)	41.0 (23.0)	43.5 (22.0)	48.0 (25.0)	47.0 (22.0)
Multiple Object Tracking Prop Score	0.74 (0.15)	0.76 (0.15)	0.76 (0.15)	0.73 (0.16)	0.75 (0.15)	0.71 (0.12)	0.76 (0.14)	0.76 (0.16)
Multiple Object Tracking Max Object Tested	5.0 (1.0)	5.0 (1.0)	5.0 (1.0)	5.0 (1.0)	5.0 (1.0)	4.5 (1.0)	5.0 (1.0)	5.0 (1.0)
Multiple Object Tracking Com Score	1,759.7 (902.4)	1,724.0 (763.3)	1,724.0 (763.3)	1,803.7 (913.1)	1,691.5 (853.2)	1,497.8 (593.6)	1,729.4 (840.5)	1,824.4 (897.7)
Multiple Object Tracking Threshold Speed	516.0 (144.0)	524.0 (132.0)	524.0 (132.0)	532.0 (144.0)	512.0 (132.0)	468.0 (102.0)	498.0 (208.0)	528.0 (136.0)
Average Reaction Time dominant hand (ms)	331.5 (43.0)*	318.5 (36.0)*	318.5 (36.0)[e,f]	332.0 (34.0)[e]	330.0 (47.0)[f]	322.5 (41.5)	325.0 (38.0)	337.0 (42.0)
Average Reaction Time non dominant (ms)	327.0 (46.5)*	318.5 (41.0)*	318.5 (41.0)	326.0 (44.0)	332.0 (50.0)	331.5 (52.5)	318.0 (41.0)	333.0 (50.0)
Average Reaction Time (ms)	329.0 (41.0)*	318.5 (36.0)*	318.5 (36.0)[g,h]	329.0 (30.0)[g]	334.0 (45.0)[h]	327.0 (42.5)	324.0 (38.0)	336.0 (44.0)
Target Capture	200.0 (50.0)	200.0 (50.0)	200.0 (50.0)	200.0 (50.0)	200.0 (50.0)	212.5 (37.5)	212.5 (75.0)	200.0 (50.0)
Eye Hand Coordination Total Time (ms)	47,352.0 (5,608.0)*	48,734.0 (5,941.0)*	48,734.0 (5,941.0)*	48,033.0 (5,023.5)	46,520.0 (5,780.0)*	47,493.0 (9,399.0)	47,186.0 (6,160.5)	47,123.0 (5,626.0)
Eye Hand Coordination Average Reaction Time (ms)	630.9 (103.8)	625.0 (106.5)	625.0 (106.5)	613.0 (98.4)	644.0 (102.6)	628.7 (129.8)	611.4 (96.5)	646.5 (88.5)
Eye Hand Coordination Central Average Reaction Time (ms)	538.4 (67.0)	540.3 (71.5)	540.3 (71.5)	539.5 (62.8)	538.4 (69.2)	543.9 (93.6)	520.3 (72.3)	543,63.0 (62.0)
Eye Hand Coordination Peripheral Average Reaction Time (ms)	671.8 (133.3)	653.09 (135.5)	653.09 (135.5)	649.68 (114.6)*	693.1 (131.0)*	655.9 (153.49)	657.7 (137.8)	697.1 (114.3)
Go/No-Go Total Score	11.0 (12.0)*	6.0 (9.0)*	6.0 (9.0) [j,k]	7.0 (9.5)[i,j]	12.0 (13.0) [i,k]	9.0 (7.5)*	11.0 (10.0)	12.0 (14.0)*

Abbreviations: mTBI, mild traumatic brain injury

*Statistically significant difference between 2 groups

[a] Near Far Quickness to near significantly slower in combat Soldiers with 1-2 mTBI versus 3+ mTBI.
[b] Near Far Quickness to near significantly slower in combat Soldiers with 0 mTBI versus 3+ mTBI.
[c] Near Far Quickness to far significantly slower in combat Soldiers with 1-2 mTBI versus 3+ mTBI.
[d] Near Far Quickness to far significantly slower in combat Soldiers with 0 mTBI versus 3+ mTBI.
[e] Average Reaction Time dominant hand significantly faster in combat Soldiers with 0 mTBI versus 1-2 mTBI.
[f] Average Reaction Time dominant hand significantly faster in combat Soldiers with 0 mTBI versus 3+ mTBI.
[g] Average Reaction Time significantly faster combat Soldiers with 0 mTBI versus 1-2 mTBI.
[h] Average Reaction Time significantly faster combat Soldiers with 0 mTBI versus 3+ mTBI.
[i] Go/No-Go significantly lower in combat Soldiers with 1-2 mTBI versus 3+ mTBI.
[j] Go/No-Go significantly lower in combat Soldiers with 0 mTBI versus 1-2 mTBI.
[k] Go/No-Go significantly lower in combat Soldiers with 0 mTBI versus 3+ mTBI.
[l] Contrast Sensitivity significantly higher in combat Soldiers with mTBI within past month versus past year.
[m] Contrast Sensitivity significantly lower in combat Soldiers with mTBI within past year versus year +.
[n] Near Far Quickness to far significantly slower in combat Soldiers with mTBI within past month versus past year.
[o] Near Far Quickness to far significantly slower in combat Soldiers with mTBI within past month versus year+.

Appendix 2

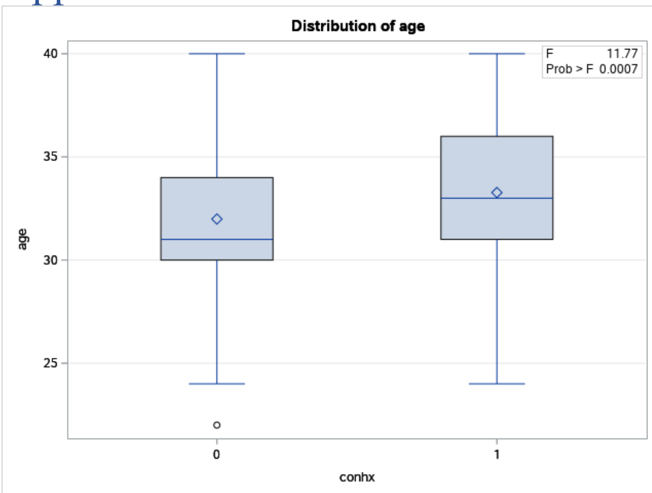


Figure 6. Distribution of age between the concussion history groups

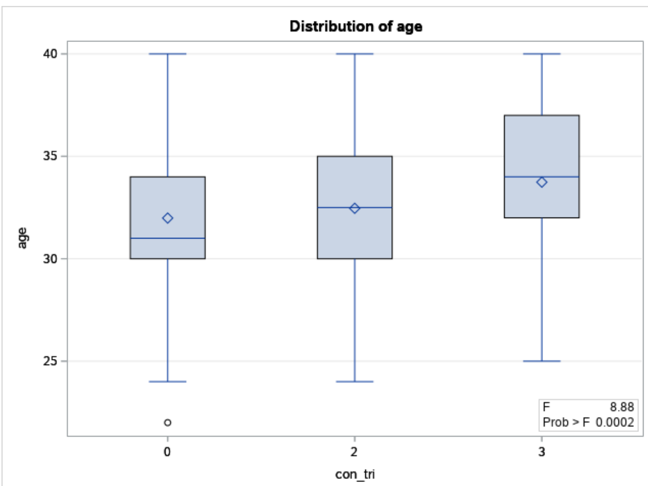


Figure 7. Distribution of age between the lifetime mTBI incidence groups

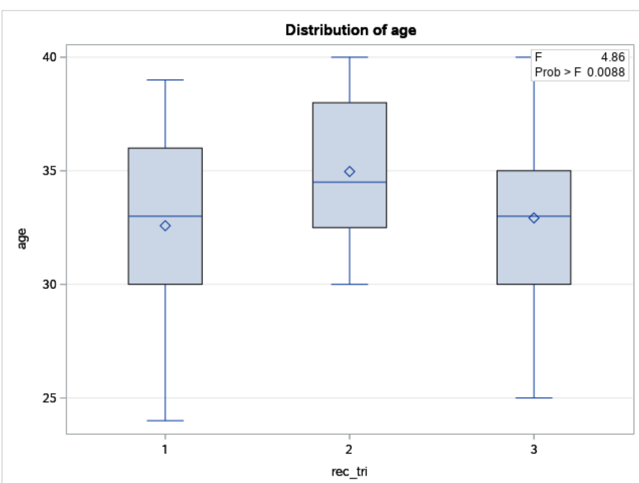
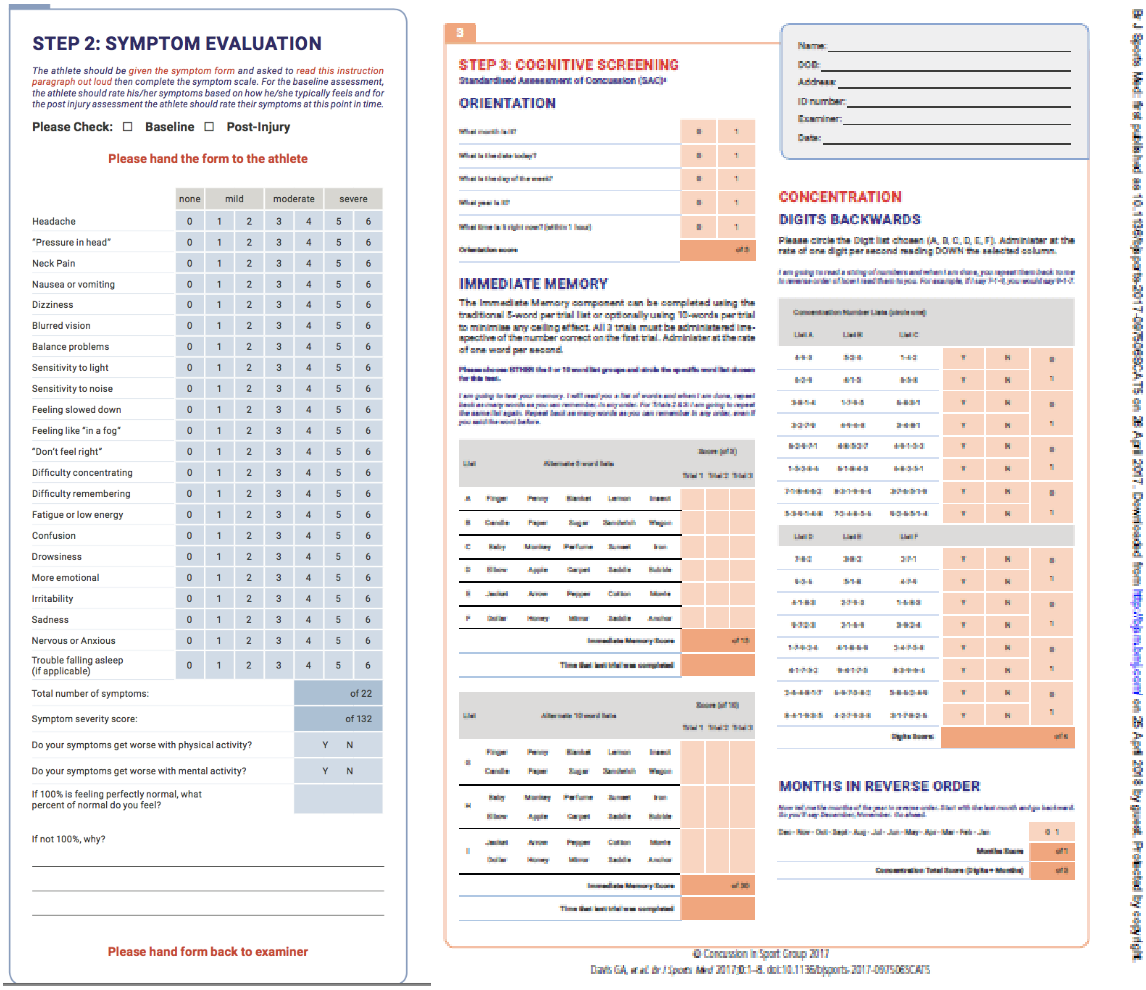


Figure 8. Distribution of age between the recency groups

Appendix 3

SCAT-5 and MACE-2



STEP 2: SYMPTOM EVALUATION

The athlete should be given the symptom form and asked to read this instruction paragraph out loud then complete the symptom scale. For the baseline assessment, the athlete should rate his/her symptoms based on how he/she typically feels and for the post injury assessment the athlete should rate their symptoms at this point in time.

Please Check: ☐ **Baseline** ☐ **Post-Injury**

Please hand the form to the athlete

	none	mild		moderate		severe	
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6
Trouble falling asleep (if applicable)	0	1	2	3	4	5	6

Total number of symptoms:	of 22
Symptom severity score:	of 132
Do your symptoms get worse with physical activity?	Y N
Do your symptoms get worse with mental activity?	Y N
If 100% is feeling perfectly normal, what percent of normal do you feel?	

If not 100%, why?

Please hand form back to examiner

STEP 3: COGNITIVE SCREENING

Standardised Assessment of Concussion (SAC)

Name:
DOB:
Address:
ID number:
Examiner:
Date:

ORIENTATION

What month is it?	0	1
What is the date today?	0	1
What is the day of the week?	0	1
What year is it?	0	1
What time is it right now? (within 1 hour)	0	1
Orientation score		of 5

IMMEDIATE MEMORY

The Immediate Memory component can be completed using the traditional 5-word per trial list or optionally using 10-words per trial to minimise any ceiling effect. All 3 trials must be administered irrespective of the number correct on the first trial. Administer at the rate of one word per second.

List	Alternate 5 word lists					Trial 1	Trial 2	Trial 3
A	Finger	Penny	Blanket	Lemon	Insect			
B	Candle	Paper	Sugar	Sandwich	Wagon			
C	Baby	Monkey	Perfume	Sunset	Iron			
D	Elbow	Apple	Carpet	Saddle	Bubble			
E	Jacket	Arrow	Pepper	Cotton	Movie			
F	Dollar	Honey	Mirror	Saddle	Anchor			
					Immediate Memory Score			of 15
					Time that last trial was completed			

CONCENTRATION

DIGITS BACKWARDS

Please circle the Digit list chosen (A, B, C, D, E, F). Administer at the rate of one digit per second reading DOWN the selected column.

MONTHS IN REVERSE ORDER

Dec - Nov - Oct - Sept - Aug - Jul - Jun - May - Apr - Mar - Feb - Jan

Months Score of 1

Concentration Total Score (Digits + Months) of 5

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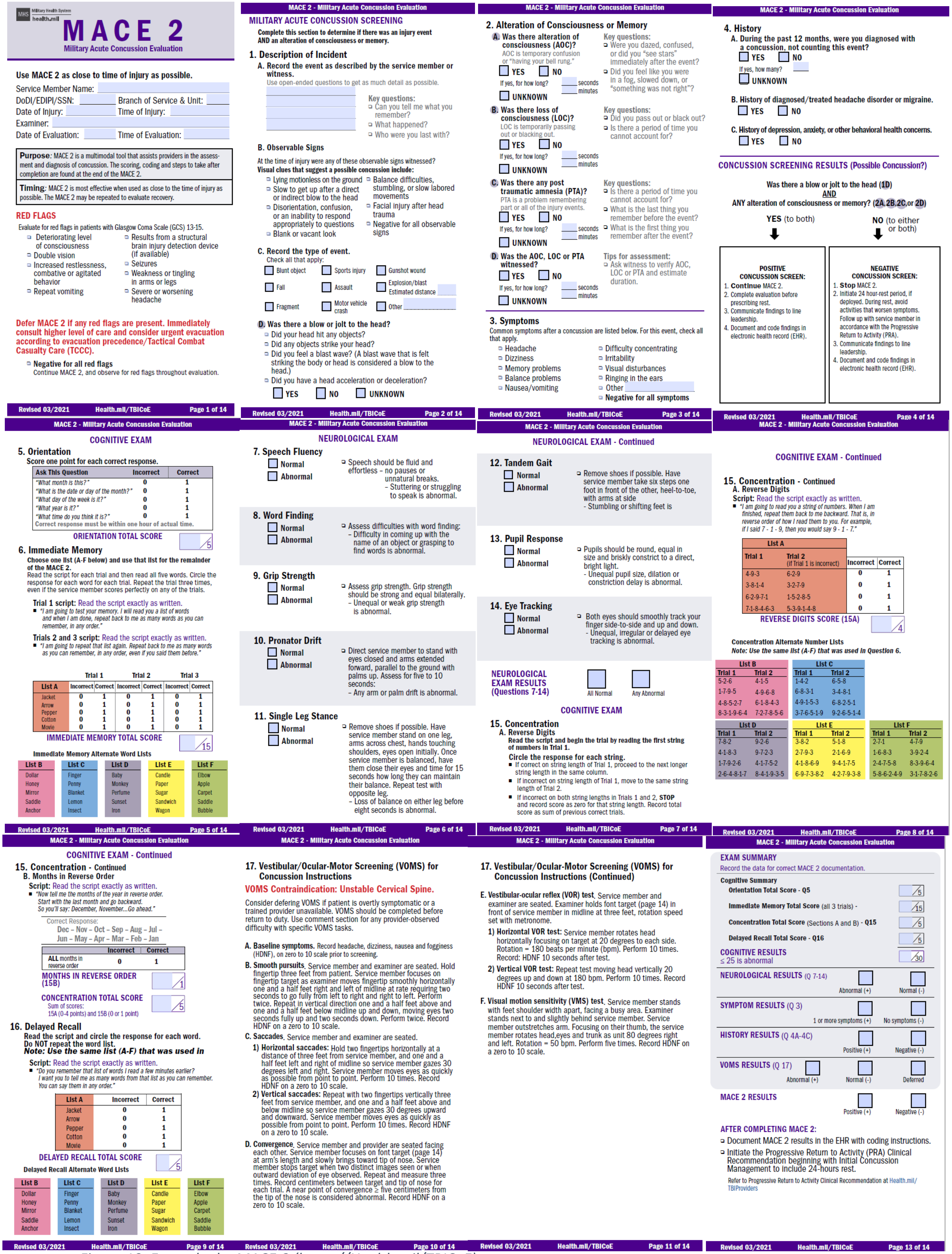
Davis GA, *et al. Br J Sports Med* 2017;0:1–8. doi:10.1136/bjsports-2017-097506SCAT5

Figure 9. Example of symptoms and cognitive portion of the SCAT-5
https://bjsm.bmj.com/



MACE 2 Military Acute Concussion Evaluation

Use MACE 2 as close to time of injury as possible.

Service Member Name:
DoD/EDIPI/SSN: Branch of Service & Unit:
Date of Injury: Time of Injury:
Examiner:
Date of Evaluation: Time of Evaluation:

Purpose: MACE 2 is a multimodal tool that assists providers in the assessment and diagnosis of concussion. The scoring, coding and steps to take after completion are found at the end of the MACE 2.

Timing: MACE 2 is most effective when used as close to the time of injury as possible. The MACE 2 may be repeated to evaluate recovery.

RED FLAGS

Evaluate for red flags in patients with Glasgow Coma Scale (GCS) 13-15.
- Deteriorating level of consciousness
- Double vision
- Increased restlessness, combative or agitated behavior
- Repeat vomiting
- Results from a structural brain injury detection device (if available)
- Seizures
- Weakness or tingling in arms or legs
- Severe or worsening headache

Defer MACE 2 if any red flags are present. Immediately consult higher level of care and consider urgent evacuation according to evacuation precedence/Tactical Combat Casualty Care (TCCC).

- Negative for all red flags
Continue MACE 2, and observe for red flags throughout evaluation.

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MILITARY ACUTE CONCUSSION SCREENING

Complete this section to determine if there was an injury event AND an alteration of consciousness or memory.

1. Description of Incident
A. Record the event as described by the service member or witness.
Use open-ended questions to get as much detail as possible.
Key questions:
- Can you tell me what you remember?
- What happened?
- Who were you last with?

B. Observable Signs
At the time of injury were any of these observable signs witnessed?
Visual clues that suggest a possible concussion include:
- Lying motionless on the ground
- Slow to get up after a direct or indirect blow to the head
- Disorientation, confusion, or an inability to respond appropriately to questions
- Blank or vacant look
- Balance difficulties, stumbling, or slow labored movements
- Facial injury after head trauma
- Negative for all observable signs

C. Record the type of event.
Check all that apply:
Blunt object / Sports injury / Gunshot wound / Fall / Assault / Explosion/blast Estimated distance / Fragment / Motor vehicle crash / Other

D. Was there a blow or jolt to the head?
- Did your head hit any objects?
- Did any objects strike your head?
- Did you feel a blast wave? (A blast wave that is felt striking the body or head is considered a blow to the head.)
- Did you have a head acceleration or deceleration?
YES NO UNKNOWN

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2. Alteration of Consciousness or Memory
A. Was there alteration of consciousness (AOC)?
AOC is temporary confusion or "having your bell rung."
YES NO If yes, for how long? seconds minutes UNKNOWN
Key questions:
- Were you dazed, confused, or did you see "see stars" immediately after the event?
- Did you feel like you were in a fog, slowed down, or "something was not right"?

B. Was there loss of consciousness (LOC)?
LOC is temporarily passing out or blacking out.
YES NO If yes, for how long? seconds minutes UNKNOWN
Key questions:
- Did you pass out or black out?
- Is there a period of time you cannot account for?

C. Was there any post traumatic amnesia (PTA)?
PTA is a problem remembering part or all of the injury events.
YES NO If yes, for how long? seconds minutes UNKNOWN
Key questions:
- Is there a period of time you cannot account for?
- What is the last thing you remember before the event?
- What is the first thing you remember after the event?

D. Was the AOC, LOC or PTA witnessed?
YES NO If yes, for how long? seconds minutes UNKNOWN
Tips for assessment:
- Ask witness to verify AOC, LOC or PTA and estimate duration.

3. Symptoms
Common symptoms after a concussion are listed below. For this event, check all that apply.
- Headache
- Dizziness
- Memory problems
- Balance problems
- Nausea/vomiting
- Difficulty concentrating
- Irritability
- Visual disturbances
- Ringing in the ears
- Other
- Negative for all symptoms

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4. History
A. During the past 12 months, were you diagnosed with a concussion, not counting this event?
YES NO If yes, how many? UNKNOWN
B. History of diagnosed/treated headache disorder or migraine.
YES NO
C. History of depression, anxiety, or other behavioral health concerns.
YES NO

CONCUSSION SCREENING RESULTS (Possible Concussion?)
Was there a blow or jolt to the head (1D) AND ANY alteration of consciousness or memory? (2A, 2B, 2C, or 2D)
YES (to both) / NO (to either or both)

POSITIVE CONCUSSION SCREEN:
1. Continue MACE 2.
2. Complete evaluation before prescribing rest.
3. Communicate findings to line leadership.
4. Document and code findings in electronic health record (EHR).

NEGATIVE CONCUSSION SCREEN:
1. Stop MACE 2.
2. Initiate 24 hour-rest period, if deployed. During rest, avoid activities that worsen symptoms. Follow up with service member in accordance with the Progressive Return to Activity (PRA).
3. Communicate findings to line leadership.
4. Document and code findings in electronic health record (EHR).

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COGNITIVE EXAM

5. Orientation
Score one point for each correct response.

Ask This Question	Incorrect	Correct
"What month is this?"	0	1
"What is the date or day of the month?"	0	1
"What day of the week is it?"	0	1
"What year is it?"	0	1
"What time do you think it is?"	0	1

Correct response must be within one hour of actual time.

ORIENTATION TOTAL SCORE /5

6. Immediate Memory
Choose one list (A-F below) and use that list for the remainder of the MACE 2.
Read the script for each trial and then read all five words. Circle the response for each word for each trial. Repeat the trial three times, even if the service member scores perfectly on any of the trials.

Trial 1 script: Read the script exactly as written.
- "I am going to test your memory. I will read you a list of words and when I am done, repeat back to me as many words as you can remember, in any order."

Trials 2 and 3 script: Read the script exactly as written.
- "I am going to repeat that list again. Repeat back to me as many words as you can remember, in any order, even if you said them before."

List A	Trial 1 Incorrect	Trial 1 Correct	Trial 2 Incorrect	Trial 2 Correct	Trial 3 Incorrect	Trial 3 Correct
Jacket	0	1	0	1	0	1
Arrow	0	1	0	1	0	1
Pepper	0	1	0	1	0	1
Cotton	0	1	0	1	0	1
Movie	0	1	0	1	0	1

IMMEDIATE MEMORY TOTAL SCORE /15

Immediate Memory Alternate Word Lists

List B	List C	List D	List E	List F
Dollar	Finger	Baby	Candle	Elbow
Honey	Penny	Monkey	Paper	Apple
Mirror	Blanket	Perfume	Sugar	Carpet
Saddle	Lemon	Sunset	Sandwich	Saddle
Anchor	Insect	Iron	Wagon	Bubble

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NEUROLOGICAL EXAM

7. Speech Fluency
Normal / Abnormal
- Speech should be fluid and effortless – no pauses or unnatural breaks. - Stuttering or struggling to speak is abnormal.

8. Word Finding
Normal / Abnormal
- Assess difficulties with word finding: - Difficulty in coming up with the name of an object or grasping to find words is abnormal.

9. Grip Strength
Normal / Abnormal
- Assess grip strength. Grip strength should be strong and equal bilaterally. - Unequal or weak grip strength is abnormal.

10. Pronator Drift
Normal / Abnormal
- Direct service member to stand with eyes closed and arms extended forward, parallel to the ground with palms up. Assess for five to 10 seconds: - Any arm or palm drift is abnormal.

11. Single Leg Stance
Normal / Abnormal
- Remove shoes if possible. Have service member stand on one leg, arms across chest, hands touching shoulders, eyes open initially. Once service member is balanced, have them close their eyes and time for 15 seconds how long they can maintain their balance. Repeat test with opposite leg. - Loss of balance on either leg before eight seconds is abnormal.

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NEUROLOGICAL EXAM - Continued

12. Tandem Gait
Normal / Abnormal
- Remove shoes if possible. Have service member take six steps one foot in front of the other, heel-to-toe, with arms at side - Stumbling or shifting feet is abnormal.

13. Pupil Response
Normal / Abnormal
- Pupils should be round, equal in size and briskly constrict to a direct, bright light. - Unequal pupil size, dilation or constriction delay is abnormal.

14. Eye Tracking
Normal / Abnormal
- Both eyes should smoothly track your finger side-to-side and up and down. - Unequal, irregular or delayed eye tracking is abnormal.

NEUROLOGICAL EXAM RESULTS (Questions 7-14) All Normal / Any Abnormal

COGNITIVE EXAM

15. Concentration
A. Reverse Digits
Read the script and begin the trial by reading the first string of numbers in Trial 1.
Circle the response for each string.
- If correct on string length of Trial 1, proceed to the next longer string length in the same column.
- If incorrect on string length of Trial 1, move to the same string length of Trial 2.
- If incorrect on both string lengths in Trials 1 and 2, STOP and record score as zero for that string length. Record total score as sum of previous correct trials.

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COGNITIVE EXAM - Continued

15. Concentration - Continued
A. Reverse Digits
Script: Read the script exactly as written.
- "I am going to read you a string of numbers. When I am finished, repeat them back to me backward. That is, in reverse order of how I read them to you. For example, if I said 7 - 1 - 9, then you would say 9 - 1 - 7."

List A Trial 1	Trial 2 (If Trial 1 is incorrect)	Incorrect	Correct
4-9-3	6-2-9	0	1
3-8-1-4	3-2-7-9	0	1
6-2-9-7-1	1-5-2-8-5	0	1
7-1-8-4-6-3	5-3-9-1-4-8	0	1

REVERSE DIGITS SCORE (15A) /4

Concentration Alternate Number Lists
Note: Use the same list (A-F) that was used in Question 6.

List B Trial 1	List B Trial 2	List C Trial 1	List C Trial 2
5-2-6	4-1-5	1-4-2	6-5-8
1-7-9-5	4-9-6-8	6-8-3-1	3-4-8-1
4-8-5-2-7	6-1-8-4-3	4-9-1-5-3	6-8-2-5-1
8-3-1-9-6-4	7-2-7-8-5-6	3-7-6-5-1-9	9-2-6-5-1-4

List D Trial 1	List D Trial 2	List E Trial 1	List E Trial 2	List F Trial 1	List F Trial 2
7-8-2	9-2-6	3-8-2	5-1-8	2-7-1	4-7-9
4-1-8-3	9-7-2-3	2-7-9-3	2-1-6-9	1-6-8-3	3-9-2-4
1-7-9-2-6	4-1-7-5-2	4-1-8-6-9	9-4-1-7-5	2-4-7-5-8	8-3-9-6-4
2-6-4-8-1-7	8-4-1-9-3-5	6-9-7-3-8-2	4-2-7-9-3-8	5-8-6-2-4-9	3-1-7-8-2-6

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COGNITIVE EXAM - Continued

15. Concentration - Continued
B. Months in Reverse Order
Script: Read the script exactly as written.
- "Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say: December, November...Go ahead."

Correct Response:
Dec – Nov – Oct – Sep – Aug – Jul – Jun – May – Apr – Mar – Feb – Jan

	Incorrect	Correct
ALL months in reverse order	0	1

MONTHS IN REVERSE ORDER (15B) /1

CONCENTRATION TOTAL SCORE /5
Sum of scores: 15A (0-4 points) and 15B (0 or 1 point)

16. Delayed Recall
Read the script and circle the response for each word.
Do NOT repeat the word list.
Note: Use the same list (A-F) that was used in Question 6.
Script: Read the script exactly as written.
- "Do you remember that list of words I read a few minutes earlier? I want you to tell me as many words from that list as you can remember. You can say them in any order."

List A	Incorrect	Correct
Jacket	0	1
Arrow	0	1
Pepper	0	1
Cotton	0	1
Movie	0	1

DELAYED RECALL TOTAL SCORE /5

Delayed Recall Alternate Word Lists

List B	List C	List D	List E	List F
Dollar	Finger	Baby	Candle	Elbow
Honey	Penny	Monkey	Paper	Apple
Mirror	Blanket	Perfume	Sugar	Carpet
Saddle	Lemon	Sunset	Sandwich	Saddle
Anchor	Insect	Iron	Wagon	Bubble

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17. Vestibular/Ocular-Motor Screening (VOMS) for Concussion Instructions

VOMS Contraindication: Unstable Cervical Spine.

Consider defering VOMS if patient is overtly symptomatic or a trained provider unavailable. VOMS should be completed before return to duty. Use comment section for any provider-observed difficulty with specific VOMS tasks.

A. Baseline symptoms. Record headache, dizziness, nausea and fogginess (HDNF), on zero to 10 scale prior to screening.

B. Smooth pursuits. Service member and examiner are seated. Hold fingertip three feet from patient. Service member focuses on fingertip target as examiner moves fingertip smoothly horizontally one and a half feet right and left of midline at rate requiring two seconds to go fully from left to right and right to left. Perform twice. Repeat in vertical direction one and a half feet above and one and a half feet below midline up and down, moving eyes two seconds fully up and two seconds down. Perform twice. Record HDNF on a zero to 10 scale.

C. Saccades. Service member and examiner are seated.
1) Horizontal saccades: Hold two fingertips horizontally at a distance of three feet from service member, and one and a half feet left and right of midline so service member gazes 30 degrees left and right. Service member moves eyes as quickly as possible from point to point. Perform 10 times. Record HDNF on a zero to 10 scale.
2) Vertical saccades: Repeat with two fingertips vertically three feet from service member, and one and a half feet above and below midline so service member gazes 30 degrees upward and downward. Service member moves eyes as quickly as possible from point to point. Perform 10 times. Record HDNF on a zero to 10 scale.

D. Convergence. Service member and provider are seated facing each other. Service member focuses on font target (page 14) at arm's length and slowly brings toward tip of nose. Service member stops target when two distinct images seen or when outward deviation of eye observed. Repeat and measure three times. Record centimeters between target and tip of nose for each trial. A near point of convergence ≥ five centimeters from the tip of the nose is considered abnormal. Record HDNF on a zero to 10 scale.

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17. Vestibular/Ocular-Motor Screening (VOMS) for Concussion Instructions (Continued)

E. Vestibular-ocular reflex (VOR) test. Service member and examiner are seated. Examiner holds font target (page 14) in front of service member in midline at three feet, rotation speed set with metronome.
1) Horizontal VOR test: Service member rotates head horizontally focusing on target at 20 degrees to each side. Rotation = 180 beats per minute (bpm). Perform 10 times. Record: HDNF 10 seconds after test.
2) Vertical VOR test: Repeat test moving head vertically 20 degrees up and down at 180 bpm. Perform 10 times. Record HDNF 10 seconds after test.

F. Visual motion sensitivity (VMS) test. Service member stands with feet shoulder width apart, facing a busy area. Examiner stands next to and slightly behind service member. Service member outstretches arm. Focusing on their thumb, the service member rotates head, eyes and trunk as unit 80 degrees right and left. Rotation = 50 bpm. Perform five times. Record HDNF on a zero to 10 scale.

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EXAM SUMMARY
Record the data for correct MACE 2 documentation.

Cognitive Summary
Orientation Total Score - Q5 /5
Immediate Memory Total Score (all 3 trials) - /15
Concentration Total Score (Sections A and B) - Q15 /5
Delayed Recall Total Score - Q16 /5
COGNITIVE RESULTS ≤ 25 is abnormal /30
NEUROLOGICAL RESULTS (Q 7-14) Abnormal (+) / Normal (-)
SYMPTOM RESULTS (Q 3) 1 or more symptoms (+) / No symptoms (-)
HISTORY RESULTS (Q 4A-4C) Positive (+) / Negative (-)
VOMS RESULTS (Q 17) Abnormal (+) / Normal (-) / Deferred
MACE 2 RESULTS Positive (+) / Negative (-)

AFTER COMPLETING MACE 2:
- Document MACE 2 results in the EHR with coding instructions.
- Initiate the Progressive Return to Activity (PRA) Clinical Recommendation beginning with Initial Concussion Management to include 24-hours rest.
Refer to Progressive Return to Activity Clinical Recommendation at Health.mil/TBIProviders

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Figure 10. Example the MACE-2 (https://Health.mil/TBICoE)

Appendix 4

Progressive Return to Activity

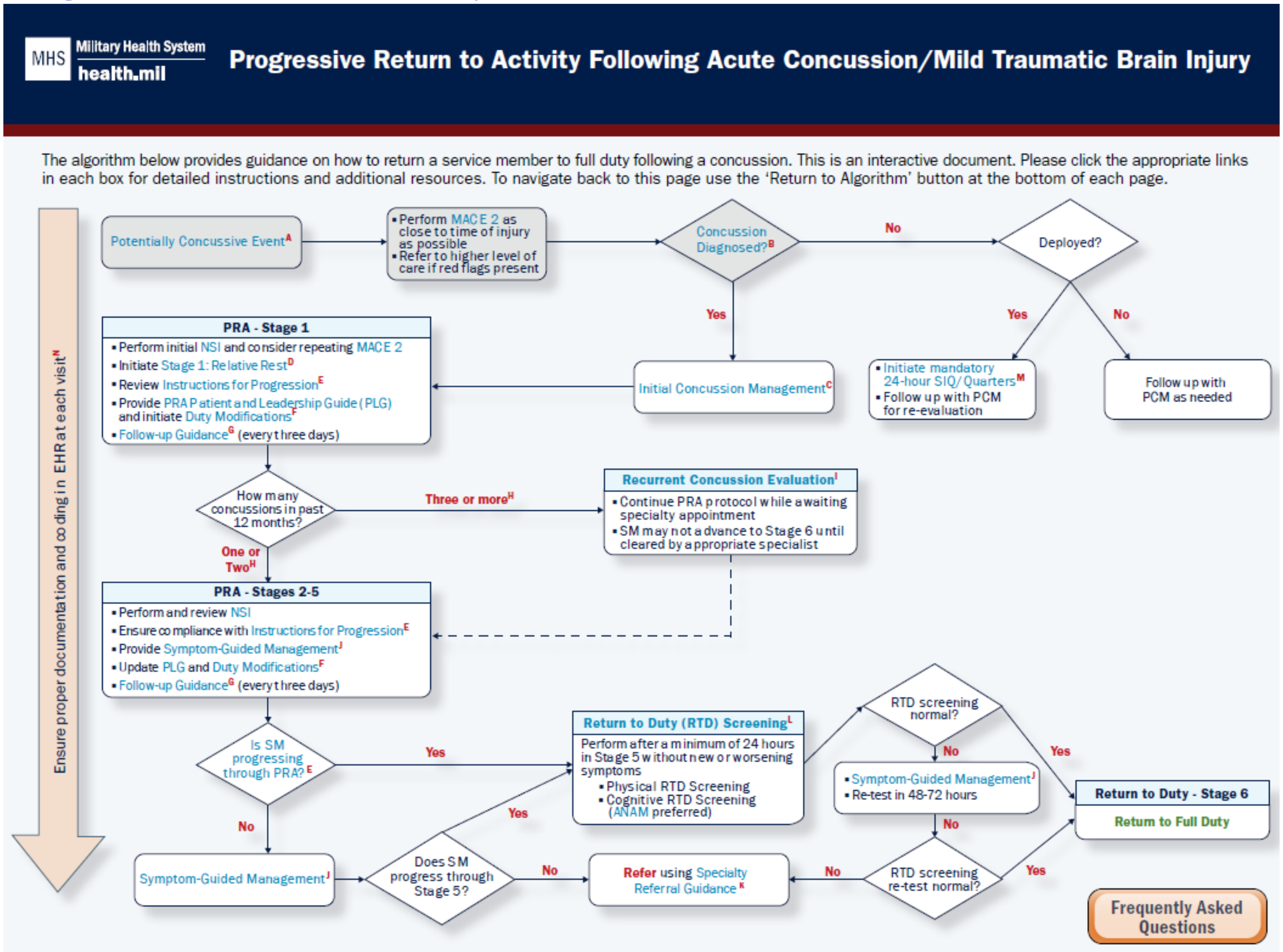

Figure 11. Progressive Return to Activity Following Acute Concussion/Mild Traumatic Brain Injury (https://health.mil)