Section Editors: Valérie Biousse, MD
Steven Galetta, MD

# Diagnostic Tests for Concussion: Is Vision Part of the Puzzle?

Rachel E. Ventura, MD, PhD, Jeffrey M. Jancuska, BA, Laura J. Balcer, MD, MSCE, Steven L. Galetta, MD

**Background:** Concussion, particularly in relation to sports and combat activities, is increasingly recognized as a potential cause of both short- and long-term neurologic sequelae. This review will focus on the neuro-ophthalmologic findings associated with concussion, the current tests for concussion, and the potential for visual performance measures to improve our detection and assessment of concussions.
**Evidence Acquisition:** A PubMed search using the specific key words "concussion," "mild traumatic brain injury," "neuro-ophthalmological findings," and "diagnostic and management tests" was performed. An emphasis was placed on articles published during the past 5 years, but additional articles referenced within recent publications were obtained.
**Results:** Concussion is frequently associated with abnormalities of saccades, pursuit eye movements, convergence, accommodation, and the vestibular–ocular reflex. Current sideline testing for athletes includes the *Sports Concussion Assessment Tool, Third Edition (SCAT3)* incorporates cognitive and balance testing. The King–Devick (K–D) test is a rapid visual performance measures that can be used on sidelines by nonmedical personnel, including parents of youth athletes. The K–D test complements components of the SCAT3 and improves the detection of concussions. Other vision-based tools for diagnosing and for managing concussion include eye movement tracking devices, pupillary assessment, computerized testing, imaging modalities, and eletrophysiologic testing. Many of the imaging modalities and electrophysiological studies have been combined with vision-based tests.
**Conclusions:** Concusssion is associated with many neuro-ophthalmologic signs and symptoms. Visual performance measures enhance the detection and management of concussion, and future studies are under way to further incorporate vision-based testing into sideline diagnosis and long-term clinical assessments.

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Traumatic brain injury (TBI) is a major cause of morbidity and mortality worldwide. The Centers for Disease Control and Prevention have estimated that there are between 1.4 and 3.8 million sports-related mild traumatic brain injuries (mTBI) annually in the United States alone, although this approximation is based on emergency room rather than outpatient visits (1–3). Concussion, a mild form of mTBI (4) (Table 1), remains underreported based on anonymous surveys of collegiate athletes (6), in part reflecting a misconception that concussion is a benign brain injury.

Concussion is defined as a direct or indirect impulse to the head or body with accompanying neurological symptoms (7, 8). Visual complaints are especially common in concussion (see **Supplemental Digital Content**, Table E1, http://links.lww.com/WNO/A135). Sustaining one concussion increases the risk of the second concussion in the same season by threefold (9) and concussed athletes who return to play before complete recovery are vulnerable to the rare, but potentially catastrophic second impact syndrome (9–11). Concussion has also been associated with long-term sequelae including neurodegenerative disorders (12–14). Given that concussions may have devastating short- and long-term effects, tools that improve our assessment and management are critical.

We will first explore deficits in visual function after concussion, which can help in both screening and monitoring the recovery of TBI symptoms. Then, we will review the most widely used concussion tests, some of which are now vision-based.

Departments of Neurology (REV, LJB, SLG), New York University School of Medicine (JMJ), New York, New York.

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Address correspondence to Steven L. Galetta, MD, 240 East 38th Street, 38th Floor, New York, NY 10016; E-mail: steven.galetta@nyumc.org

**TABLE 1.** Glossary

| Term | Definition |
|---|---|
| Mild TBI | TBI is considered mild where there is a normal CT brain, GCS (13–15), loss of consciousness <30 minutes, alternation of mental state <24 hours, and posttraumatic amnesia <24 hours. |
| TBI | An alteration in brain function, or other evidence of brain pathology, caused by an external force (4) |
| Concussion | A complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces. Common features include |
| | A direct or indirect blow to the head, face, neck, or elsewhere on the body with a force transmitted to the head |
| | The rapid onset of short-lived impairment of neurologic function that resolves spontaneously |
| | Acute clinical symptoms largely reflect a functional rather than structural disturbance, although there may indeed be neuropathological changes or abnormalities on advance imaging |
| | A graded set of clinical symptoms that may or may not involve loss of consciousness |
| | No abnormality on standard structural neuroimaging studies (5) |

TBI, Traumatic Brain Injury; CT, computed tomography; GCS, Glasgow Coma Scale.

## VISUAL FUNCTION DEFICITS IN CONCUSSION

The cognitive control of eye movements requires pathways involving fronto–parietal circuits and subcortical nuclei (15), many of which are particularly vulnerable to concussion. Common neuro-ophthalmic findings in concussion include abnormalities in saccades/antisaccades, smooth pursuit, vergence, accommodation, the vestibular–ocular reflex, and photosensitivity (Table 2). In the first 10 days after mTBI, patients have been found to have impaired antisaccades, prolonged saccadic latencies, higher directional errors, poorer spatial accuracy, and impaired memory-guided saccades (16,17). Patients with postconcussive syndrome 3–5 months after their injury perform worse on antisaccade testing, memory-guided saccades, and a self-paced saccade test in which subjects look back and forth between two points as rapidly as possible, when compared with patients who have had mTBI and recovered well (18). In addition, the gap saccade test has been studied in which subjects fixate on a central target and then, after varying amounts of time, fixate on a peripheral target. Patients with acute mTBI had longer saccadic reaction times when there is a short temporal gap between the central and peripheral targets, but not when the temporal gap is longer, suggesting difficulties in disengaging attention (19). These studies demonstrate abnormalities in saccadic function with concussion that, in part, relate to impairments in executive function (as probed with antisaccade tests), attention (as with the gap saccade test), and memory (as with memory-guided saccade tests) (Table 2) (16–20). Symptom resolution often corresponds with return of normal saccadic function (18). These saccadic tests have been studied in the research setting and require the use of a computer and video-oculography and thus have limited clinical application at this time. The absence of baseline testing, calibration issues, poor attention, and medication effects could be other issues that complicate the routine testing of eye movements. Saccadic dysfunction as assessed clinically may be present in approximately 30% of patients with mTBI (21).

Smooth pursuit requires attention, anticipation, and working memory as well as smooth and at times, saccadic eye movements to fixate on a moving target (22). Suh and colleagues (23,24) correlated mTBI with decreased target prediction, increased eye position error, and variability of eye position using a circular tracking test. Temporarily extinguishing the target, which necessitates more predictive tracking, resulted in more abnormal findings. When tested clinically, it was found that 60% of mTBI patients had abnormalities in pursuit eye movements (21).

Convergence abnormalities have been reported in 47%–64% of patients with concussion (21,25). Additionally, 65% of concussed patients vs. only 15% of controls have abnormalities in accommodative amplitude (21). Patients with sports-related concussions often have symptomatic complaints attributable to either convergence or accommodative insufficiency, such as headaches, "sore eyes," words coming in and out of focus, and losing one's place while reading (21). Peripheral and central mechanisms of vertigo also commonly occur with concussions. In addition, patients often complain of increased light sensitivity, which is possibly due to meningeal irritation, migraine, or driven through central pathways such as the thalamus (26). Ocular motor palsies and other cranial nerve abnormalities are unlikely to occur in concussion as opposed to more severe forms of TBI, and their presence with concussion should alert the examiner to look for a preexisting structural abnormality such as an arteriovenous malformation, aneurysm, or tumor (27).

Testing individual eye movements is important, but requires clinical expertise which may limit widespread use on the sideline, particularly at the youth level where sports parents will be in charge of concussion assessment. Cost, standardization, accessibility, and reliability will be other considerations when developing sideline tools for concussion evaluation.

**TABLE 2.** Tests of saccades and pursuit can be used to assess higher cognitive functions using research paradigms.

Research Paradigms for Assessing Higher Cognitive Functions while Testing Saccades and Smooth Pursuit

| Eye Movement Type | Higher Cognitive Function Tested | Paradigms Involving Eye Movements | How the Research Paradigms are Performed |
|---|---|---|---|
| Saccades | Attention | Gap Saccade Test | Subject fixates on one target which then extinguishes and the subject orients to a peripheral target after a variable period |
| | | Visually Cued Saccades | Subject fixates on a central target and then a cue indicates the possible location of an upcoming target, then a congruent or incongruent target to the cue appears and saccades generated |
| | Executive Function | Antisaccades | Subject is asked to look away from the target presented |
| | | Memory-guided Saccades | Subject focuses on a central target and then a peripheral target briefly appears; after a variable delay the subject is asked to fixate by memory on where the peripheral target was located |
| | Memory | Memory-guided Sequences | The subject is presented with targets on a screen and then asked to memorize the sequence in which they are illuminated, and then on cue, they are to make saccades in the memorized order |
| Smooth Pursuit | Memory | Smooth pursuit of a predictive target | Subject tracks an object on a known trajectory, for example, a circle, and the object may at times be transiently extinguished on its course |
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## CONCUSSION TESTS

Concussion tests can be divided into those used for diagnosis and initial assessment, including symptom checklists and sideline evaluations, and those used for management, including computerized neurocognitive testing, neuroimaging, biomarkers, and electrophysiology.

### Symptom Checklists

Symptom checklists rely on self-reporting among a list of symptoms (see **Supplemental Digital Content**, Table E2, http://links.lww.com/WNO/A136) and as such are susceptible to underreporting (28). In an online survey of 262 University of Pennsylvania athletes, 43% of participants with a history of concussion have hidden symptoms to stay in a game (6). Apart from suffering from potentially inaccurate reporting, symptom checklists may have a limited role in return-to-play guidelines because cognitive impairment may persist beyond symptom resolution (29), although they are helpful in monitoring recovery. Mucha and colleagues (30) have recently described a screening test, called the Vestibular/Ocular Motor Screening Assessment, in which symptoms are reported while subjects undergo a battery of vestibular and ocular provocations. They found that subjects who reported symptoms with the provocations of undergoing vestibular–ocular reflex testing or testing visual motion sensitivity were highly likely to be in the concussed group with an odds ratio of 3.89 and 3.37, respectively. Thus provoked symptoms may be a more accurate way to assess patients with possible concussions, but this methodology still suffers from biases inherent in patient self-reporting. Combining provoked symptoms with any objective findings on the vestibular and ocular examination may increase the likelihood of predicting subjects with concussion and also provide clues regarding inaccurate reporting.

### Sideline Tests

**King–Devick (K–D) Test**

Since approximately 50% of the brain's circuits are related to vision (31), and many of these pathways are susceptible to injury in concussion, performance measures involving visual function are promising in sideline assessment. To perform the K–D test, the subject rapidly reads numbers on three test cards, with the score being the total time required in seconds (see **Supplemental Digital Content**, Figure E1, http://links.lww.com/WNO/A133). This typically takes 1–2 minutes. Rapid number naming requires a distributed network of saccade areas including those in the dorsolateral prefrontal cortex (DLPFC) that are responsible for anticipatory saccades (15,32). The K–D test also requires attention and language, as well as other areas involved in reading; K–D thereby tests functioning of the brainstem, cerebellum, and cerebral cortex (33,34). Eye movement abnormalities commonly occur with concussion and the K–D test allows them to be assessed without the clinical expertise that would otherwise be required. Like any functional test, K–D baseline scores can be potentially limited by those athletes who willfully attempt to sandbag the test. Understanding the typical range of scores and encouraging the athlete to read as fast as they can limit such activity. Factors that may limit sandbagging of functional tests is an important area for future investigation.

Studies of mixed martial arts fighters, boxers, collegiate athletes, professional hockey players, and rugby players consistently reveal on average a 5- to 7-second increase (worse) score immediately after concussion compared with baseline (33–36). Any worsening of the K–D score from baseline suggests the presence of a concussion (33–36). Scores are not worsened by routine exercise, and there is a learning effect with repeated testing (33). Furthermore, a control cohort studied at the same time as the concussed athlete group showed an improvement of K–D times. Given that other sideline tests such as the Standardized Assessment of Concussion (SAC) and Balance Error Scoring System (BESS; see below) do not assess eye movements, we studied whether the K–D would provide additional information in a cohort of University of Florida athletes (5). We found that the SAC and BESS even when used together as sideline tools failed to show abnormalities in 10% of the 20 concussions under study. With the addition of the K–D, all of the concussions could be identified. Thus, adding the K–D increased our ability to detect concussed athletes and complements the SAC and BESS as a performance measure.

### Sport Concussion Assessment Tool, Third Edition (SCAT3)

The SCAT3 is a commonly used sideline tool that consists of a 22-item symptom checklist, cognitive and physical examination, the Glasgow Coma Scale, Maddocks questions (set of 5 questions that assess game-specific orientation and recent memory) (37, 38), the modified BESS, and the SAC. The SCAT3 takes 15–20 minutes to complete and was compiled by a consensus committee based on best available measures (39). A composite score reflects the quantity of questions in each section rather than the importance and may not be as helpful as using each component alone (39). Baseline testing is required due to individual variability (40–42). The SCAT3 does not test all areas, such as vision, limiting its use as a sole indicator for concussion diagnosis or for return-to-play, although it can provide supportive information (43). The lack of a vision test in the SCAT3 is a current gap despite its widespread use a sideline concussion tool.

### Standardized Assessment of Concussion

The SAC is a component of SCAT3 that measures cognitive areas including orientation, immediate memory, concentration, and delayed recall (Fig. 1) (44–48). In one study, only 50% of 28 concussed collegiate athletes had abnormal SAC testing. The test was able to capture some concussed athletes with normal BESS and K–D scores and seems to have value as a complementary test (5). One should note that the scores may be artificially inflated since athletes can memorize sections of the test (49).

### Balance Error Scoring System and Other Tests of Balance

The BESS, another component of the SCAT3, tests balance (see **Supplemental Digital Content**, Figure E2, http://links.lww.com/WNO/A134). Likely due to its subjective nature, there is a great variability in scoring for the BESS. The interrater reliability intraclass correlation (ICC) has been reported as 0.57, with intrarater reliability ICC's of 0.74 (50). Given this variability, particularly between raters, it is prudent to have the same individual measure baseline and postconcussive BESS scores when possible. Performance on the BESS also can vary over the course of the season, as it is affected by the sport played, history of ankle injury, and fatigue (51–55).

**Components of the Standardized Assessment of Concussion Test**

**Orientation** (1 point for each correct answer, 5 possible points total)

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

**Immediate memory** (1 point for stating each of 5 words over 3 trials for a total of 15 possible points)

| | Alternate words: | | |
|---|---|---|---|
| Elbow | candle | baby | finger |
| Apple | paper | monkey | penny |
| Carpet | sugar | perfume | blanket |
| Saddle | sandwich | sunset | lemon |
| Bubble | wagon | iron | insect |

**Concentration: Digits Backward** (1 point for completing each of the digit series backwards, for a total of 4 possible points)

| | Alternate digit list: | |
|---|---|---|
| 4-9-3 | 6-2-9 | 5-2-6 |
| 3-8-1-4 | 3-2-7-9 | 1-7-9-5 |
| 6-2-9-7-1 | 1-5-2-8-6 | 3-8-5-2-7 |
| 7-1-8-4-6-2 | 5-3-9-1-4-8 | 8-3-1-9-6-4 |

**Concentration: Months in Reverse Order** (1 point for entire sequence correct)

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

**Delayed Recall** (total possible 5 points)

**FIG. 1.** Standardized assessment of concussion test examines orientation, memory, and concentration function (42). Total possible of 30 points.

Portable inertia sensors may help to obtain more objective and sensitive measures of balance. One study found that although the BESS alone could not distinguish controls from those with a recent history of concussion and balance complaints, the addition of a portable inertia sensor enabled detection of significant differences (56). Additionally, Wii Balance Boards provide another objective balance test and have been shown to have improved validity (0.99) and test–retest reliability (0.88) over the BESS (57).

**Head Impact Telemetry System**

Head impact telemetry system is an investigational tool in which a series of accelerometers incorporated into the padding of a football helmet provide data on the magnitude and location of impact (58). Factors such as a rotational acceleration greater than 5500 radians per second, linear acceleration greater than approximately 96 g, and location of impact can be predictive for concussion (58). By analyzing these measurements on the field, athletes at risk for concussive injury could potentially be identified, many of whom may show evidence of structural compromise using diffusion tensor imaging (DTI) even without a clinical presentation (59). Individuals with impacts below the predicted concussion threshold can still have a concussion, making complementary assessments necessary (49).

### *Eye Movement Tracking Devices*

Use of a portable head-mounted video-based eye tracker to detect abnormalities in eye movements has been studied in the research setting on a limited basis. Cifu and colleagues (60) recently reported use of an eye tracking device on 60 military subjects with persistent concussive symptoms vs. 26 controls and found that those with the concussive symptoms had significantly larger saccadic position errors, smaller saccadic amplitudes, smaller predicted peak velocities, smaller peak accelerations, and also abnormalities in pursuit velocities. Further work is required to determine how acutely these eye movement changes occur and the exact time course for recovery.

### *Immediate Postconcussion Assessment Cognitive Test and Other Computerized Neurocognitive Tests*

Immediate postconcussion assessment cognitive test (ImPACT) is a computerized neuropsychological test battery that takes 20 minutes to complete. Deficits detected by ImPACT correlate with traditional neuropsychological testing (61) and with functional magnetic resonance imaging (fMRI) findings such as altered activation of the DLPFC (62). Visual subscores on ImPACT correlate with the K–D test (5). The software incorporates statistical techniques to account for normal test score variability over time and can usually detect intentional "sandbagging" by flagging athletes with scores on certain subscales that are below predefined values (63,64). Meaningful postinjury ImPACT results require baseline testing (65,66), since factors such as attention-deficit hyperactivity disorder and learning disabilities affect baseline scores (67). Eighty-three percent of athletes with concussion who completed the ImPACT battery did show cognitive impairment, although it is notable that 17% of those with concussion did not show any abnormality on the cognitive measures (68) and that up to 20%–40% of nonconcussed athletes demonstrated cognitive impairment (61,69,70). One should be cautious in the use of ImPACT in return-to-play decisions, given insufficient validity and test–retest reliability, and also because subjects may have ongoing metabolic abnormalities in spite of return of ImPACT scores to baseline (71). Other computerized programs have emerged, and further study of their ability to detect and guide return to play need to be performed. Computerized testing has its limitations and should be used by those skilled in the interpretation of such testing.

## *Neuroimaging*

**Conventional Magnetic Resonance Imaging and Computed Tomography**

A commonly accepted definition of mTBI/concussion requires normal computed tomography imaging. Routine magnetic resonance imaging (MRI) is often normal as well (72,73), although susceptibility-weighted imaging sequences can detect microhemorrhages associated with subconcussive or concussive injury (74). One prospective study found that 4 of 19 patients with mTBI had brain atrophy as measured by MRI volumetry 3–7 months postinjury. However, this was a small study, and it did not include patients with sports-related concussions (75). Another study found that collegiate football players had decreased hippocampal volumes vs. controls, with an inverse relationship between left hippocampal volume and years of football played (76). Among the football players, those with a history of concussion had the smallest hippocampi (76).

**Diffusion tensor imaging**

DTI maps the diffusion of molecules, mainly water (77). Fractional anisotropy is a measurement of the fraction of diffusion magnitude (78) and has been shown to be a reliable marker of white-matter integrity (72,79). Significant DTI findings in players with a history of concussion compared with nonconcussed controls include widespread increase in fractional anisotropy and decreased trace and radial diffusivity in the right corona radiata, right posterior limb of the internal capsule, right superior temporal white matter (80), and optic radiations (81).

Maruta and colleagues (73) used video-oculography to record visual tracking of a moving target in a circular trajectory combined with DTI analysis of their concussed subjects. They found that large gaze error variability was associated with low fractional anisotropy values in areas known to be frequently compromised in concussion, such as the right anterior corona radiata, the left superior cerebellar peduncle, the genu of the corpus callosum, and a number of other brain regions.

DTI also has been studied in subjects with subconcussive impacts. In one study, nonconcussed athletes in contact sports were found to have significant changes in mean diffusivity in the corpus callosum and fractional anisotropy in the amygdala when compared with athletes in noncontact sports over the course of one season. Measurements of head impact detected with a helmet sensor correlated with changes in white-matter diffusivity in several brain regions, in spite of not having a clinical concussion (59). These studies highlight a role for DTI in further delineating the pathology associated with concussive or subconcussive brain injuries.

#### Functional Magnetic Resonance Imaging

Blood-oxygen-level-dependent (BOLD) fMRI detects changes in the oxygenation state of hemoglobin, thereby capturing oxygen consumption associated with neuronal activation (79). With concussion, changes in brain activation using fMRI are observed acutely and several months after injury even without clinical changes (82–87). Patients with severe postconcussion symptoms have increased activity in the normal working memory network that correlates with symptom severity (88,89). Conversely, patients with concussion have reduced activation in the DLPFC, insular cortex, anterior cingulate cortex, striatum, and medial frontal and temporal regions (90). Functional MRI studies on mTBI patients with concussion who were performing a visual working memory task showed decreased BOLD signal intensities in the right mid-DLPFC, which corresponded to severity of their postconcussive symptoms (91). However, one caveat is that it can be challenging to interpret fMRI changes given the complexity of neuronal circuitry (92).

#### Magnetic Resonance Spectroscopy

Magnetic resonance spectroscopy (MRS) measures the concentrations of molecules associated with brain metabolism (72,79). Concussion significantly lowers levels of gray matter glutamine and *N*-acetylaspartate (NAA) and increases levels of white matter creatine (Cr) and choline (Cho) (72,93,94). MRS studies on one cohort of patients with concussion who had symptom resolution in about 3 days found that it took 30 days for the NAA level and NAA/Cr ratio to return to baseline (94). Another study of patients with concussion who required about 15 days for symptomatic clinical recovery found that it took 45 days for the NAA/Cho ratio to return to baseline (95). MRS holds promise clinically in determining metabolic recovery from concussion and aiding in return-to-play decisions (94).

#### Positron Emission Tomography

Positron emission tomography (PET) scanning uses radiolabeled metabolic analogs to measure the rate of brain glucose metabolism (72,79). Mild TBI decreases glucose metabolism in the cerebellar vermis, pons, and medial temporal cortex (96). Decreases in glucose metabolism in concussed patients were found to correlate with cognitive disturbances (97). Further research is necessary to validate these studies and determine the potential clinical utility of PET scanning, with the ultimate goal of identifying individuals at risk for worse outcomes or neurodegeneration (98).

### *Electrophysiology*

Concussion leads to abnormal electrical activity, such as smaller amplitudes of frontal N350 and parietal P300 evoked responses (99,100). Patients with multiple concussions have been found to have abnormal electrophysiological results even 2–3 years after their last injury, well after symptoms have resolved. This has been shown when patients perform a visual spatial attention and short-term memory task (101). Electrophysiological techniques, particularly when paired with visual tasks, provide insight into subclinical postconcussive abnormalities and may help to predict those vulnerable to long-term sequelae.

## CONCLUSIONS

Concussion and mTBI have a multitude of effects on the visual system, necessitating a careful neuro-ophthalmic examination. Clinically, tests of saccades, pursuit, convergence, accommodation, vestibular–ocular reflex, and ocular misalignment are frequently abnormal. Sideline tests of visual performance, such as the K–D test, may be a sensitive means of screening for sports-related concussion. As a visual performance measure with an objective end point, this tool can be administered at the sideline by a nonprofessional.

The armamentarium for assessing concussion is largely under development. Tests under exploration for assessing long-term sequelae of mTBI include ocular coherence tomography, as it has been found that mice with blast injury have a decrease in the retinal nerve fiber layer 3 months postinjury (102). Other devices measuring afferent and efferent visual dysfunction are currently being developed, but their cost, efficiency, and need for expert interpretation may limit their widespread use.

Vision has also garnered attention for potential use in predicting subjects at risk of more severe head impacts. Harpham and colleagues (103) found that those athletes with low visual and sensory performance, including on such tasks as depth perception and visual reaction time, had a higher number of more severe impacts measured using head impact telemetry. This raises the question as to whether visual training can decrease the likelihood of severe head impacts, and further study in this area is ongoing.

We have highlighted the merits of many of the currently used tests, but, at present, there is no single test that alone can reliably diagnose concussion or determine when recovery has occurred. Clinical decision making based on examination and assessment of a wide variety of tools is still necessary. Given the potentially devastating long-term effects of repeated head trauma, it is important to be able to accurately assess even subclinical brain injury. A combination of visual processing tasks, neuroimaging, serum biomarkers, and electrophysiological recordings may allow further insights into subtle damage that has occurred from concussion and future clinical implications.

STATEMENT OF AUTHORSHIP

*Category 1:* a. Conception and design: Steven L. Galetta. b. Acquisition of data Rachel E. Ventura, Jeffrey Jancuska. c. Analysis and interpretation of data: Rachel E. Ventura, Steven L. Galetta. *Category 2:* a. Drafting the manuscript: Rachel E. Ventura, Jeffrey Jancuska. b. Revising it for intellectual content: Rachel E. Ventura, Steven L. Galetta, Laura J. Balcer. *Category 3:* a. Final approval of the completed manuscript: Rachel E. Ventura, Steven L. Galetta, Laura J. Balcer, Jeffrey Jancuska.

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