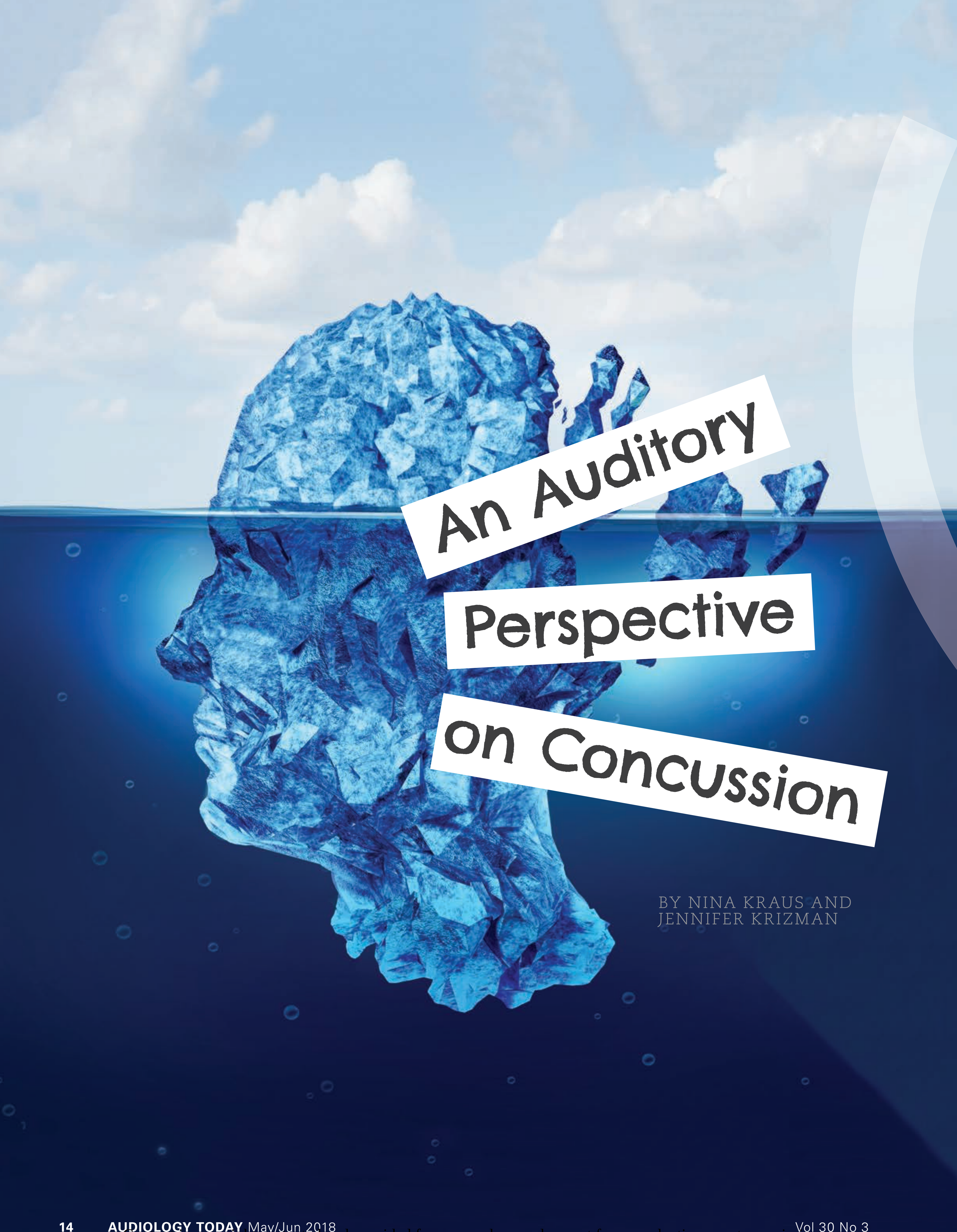

An Auditory Perspective on Concussion

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CONCUSSIONS ARE a public health crisis. Millions of athletes and thousands of service members a year, for instance, suffer concussive injuries. While more widely known to lead to possible major brain-related problems, such as CTE, concussions also damage the auditory brain, hence the auditory system should also be considered in concussion management.

Americans love football. In early February, more than 100 million viewers tuned in to the Super Bowl to watch the Philadelphia Eagles battle the New England Patriots. Despite a decline of about 7 percent in viewers from the 2017 Super Bowl, this event, like in years past, will likely be the most-watched television event of the year. In fact, Super Bowl viewership can more than double its closest competitor, typically a presidential address or debate.

Why do we love football? Some say it's the violence, that the highlight-reel tackles are what draw in the crowd. And w-e convinced ourselves we were watching a violence that had no consequences. The common thought was that modern helmets and padding prevented players from serious harm and if a player suffered a concussion, the injury was no big deal—the athlete could easily bounce back.

Times have changed. We now know that concussions, though considered mild in comparison to other types of head injury, can have serious—and potentially lasting—consequences for brain health.

What Is a Concussion?

A concussion is a diffuse, nonpenetrating traumatic brain injury (TBI) caused by a sudden external force. TBIs are classified as mild, moderate, or severe, and by definition a concussion is a mild TBI. Although there has been debate over whether a "concussion" is a type

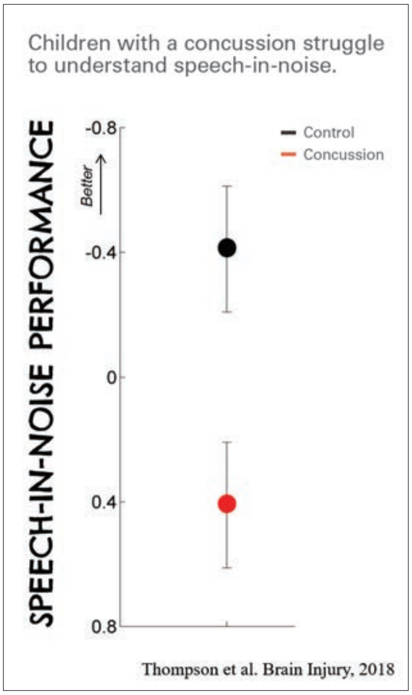


FIGURE 1. During the acute stage of recovery from a sports-related concussion, children have a harder time understanding sentences in noise compared to peers with musculoskeletal injuries.

of injury that is distinct from a "mild TBI," we recognize these terms to be synonymous, in accordance with the Defense and Veterans Brain Injury Center (DVBIC, 2018) and Centers for Disease Control and Prevention (CDC, 2018).

> Individuals diagnosed with a sports-related concussion also report auditory complaints.

Symptoms of a concussion are classified into four categories: cognitive impairments, such as difficulty concentrating; physiological impairments, such as blurry vision; emotional problems, such as feelings of sadness or depression; and sleep disturbances. Type and severity of these symptoms can vary substantially, and the same force that causes a concussion in one individual may not cause a concussion in another. Previously, loss of consciousness at the time of injury was required for a concussion diagnosis. However, it is now estimated that consciousness is maintained in about 95 percent of cases, suggesting that a substantial number of concussions may have gone undiagnosed under the previous definition.

Concussions Are a Public Health Crisis

In the United States, 1.6 million to 3.8 million sports-related concussions occur annually. Participants of contact sports such as football or boxing can also experience "subconcussive" injuries. These injuries are not severe enough to cause acute concussion symptoms, but the accrual of concussive and subconcussive events over time are believed to lead to progressive brain atrophy, a disease known as Chronic Traumatic Encephalopathy, or CTE. This neurodegenerative injury, which often does not begin until years after the athlete has stopped playing, leads to mood disorders, cognitive decline, and dementia. For example, Aaron Hernandez, the former NFL tight end convicted of murder in 2015, was found to have one of the most severe cases of CTE when he committed suicide at age 27.

There is no way to know when Hernandez's brain began to deteriorate because CTE can only be diagnosed postmortem; and, there is no way to determine if a player, still active in his or her contact sport, has experienced a "safe" number of hits or eventually will develop CTE.

Concussion, too, is an invisible injury. Because it affects function, not macrostructure, a concussion is undetectable using conventional imaging methods such as MRI or CAT scans. For this reason, concussion diagnosis relies heavily on a patient's symptom reporting. For many professional athletes in contact sports, however, their jobs are tied to their ability to sustain hits to the head and so they may try to hide or downplay a head injury to prevent losing their job to another player. This can make sports-related concussion difficult to diagnose.

To overcome the limitations of concussion diagnosis, research has shifted to identifying markers of concussion in oculomotor and vestibular function to provide objective metrics for concussion diagnosis and monitoring. Our work suggests that the auditory system should also be considered in concussion management.

Concussions Are a Military Health Crisis

For today's military, concussions have been named the signature invisible injury of war. Since 2000, nearly 300,000 service members have been diagnosed with a concussion, yet this may underrepresent the true prevalence of concussion in the military. A chief source of concussion is from blast exposure, often resulting from an improvised explosive device, or IED. When a concussion is caused by a blast exposure, other injuries that mask the concussion can occur. For example, post-traumatic stress disorder, or PTSD, is commonly diagnosed in blast-exposed veterans. Because PTSD also can lead to sleep disturbance or anxiety, it is difficult to determine if the blast exposure resulted in PTSD, concussion, or both.

What Does Concussion Have to Do with Hearing?

Simply put, concussion impairs the auditory brain.

The blast wave of an explosive device often results in damage to both the peripheral and central auditory system. Peripheral injuries include perforation of the tympanic membrane, tinnitus, temporary or permanent audiometric threshold shifts, and otalgia. However, the level of peripheral hearing damage does not align with the level of listening difficulties experienced, suggesting that the central auditory system is impaired by the concussive force of the blast wave. For example, nearly half of the blast-exposed veterans treated for concussion at VA hospitals and clinics complained of hearing difficulty, yet only 35 percent of these patients showed elevated audiometric thresholds (Myers et al, 2009). For the remaining 65 percent, the hearing problem did not lie in the ear. Furthermore, veterans with blast exposure who displayed normal audiometric thresholds performed more poorly than veterans without blast exposure on listening skills, including speech perception in noise, speech segregation, and auditory temporal resolution (Gallun et al, 2012). Even after a minimum of four years following blast exposure, veterans struggled on tests of temporal resolution, speech segregation, and temporal pattern perception, despite normal audiometric thresholds (Gallun et al, 2016). These findings align with the broader literature, which shows that the audiogram is not always a predictor of listening abilities, and that the auditory brain is a major contributor to listening abilities across the lifespan.

It's not just when a blast wave causes a concussion that listening problems arise. Individuals diagnosed with a sports-related concussion also report auditory complaints, including ringing in the ears, an inability to ignore distracting sounds or remember and follow oral directions, and difficulty understanding speech in a noisy environment, such as a restaurant or cafeteria (Lew and Guillory, 2007; Musiek et al, 2004; Turgeon et al, 2011). Speech-in-noise difficulties have been observed in concussed adults (Hoover et al, 2017; Vander Werff and Rieger, 2017), and university athletes with a history of concussion were found to perform more poorly than athletes without concussion history on tests that required integrating auditory information binaurally (Turgeon et al, 2011). We have found that during the acute stage of recovery from a sports-related concussion, children have a harder time understanding sentences in noise compared to peers with musculoskeletal injuries (Thompson et al, 2018). We also see that performance on the test declines over time for the concussed children, in contrast to a steady performance by their peers, suggesting that both fatigue and auditory processing problems affect speech-in-noise abilities in concussed children (FIGURE 1).

Why Would the Auditory System Be Affected by Concussion?

The anatomy of the auditory system makes it susceptible to injury. The auditory system has more relays connecting the sensory organ to the brain than other sensory systems and contains some of the longest axonal tracts (e.g., the lateral lemniscus). Axons bidirectionally link each of the auditory relays, traversing between the ear, brainstem, midbrain, and cortex. In addition to blood vessels, axons are believed to bear the brunt of damage from a concussive force. When a force, such as a blast wave or sports-related impact, jostles the brain inside the skull, axons are stretched and sheared by this movement. Shearing and stretching of axons can initiate a dysfunctional metabolic cascade (Giza and Hovda, 2014), which can lead to improper signaling among cells, or potentially death of the injured axon.

The susceptibility of axons to mechanical force, together with the complex interconnectivity of the auditory system and length of auditory axons, make the auditory system a likely site of dysfunction following a head impact. Indeed, axons in the auditory midbrain degenerate following a TBI, even when the force is mild (Jane et al, 1985). The positioning of the auditory cortex in the temporal lobe additionally makes it susceptible to contusions and swelling (Fausti et al, 2009; Taber et al, 2006).

How Does a Concussion Affect the Auditory Brain?

Sound processing is one of the most computationally demanding tasks the nervous system has to perform. It relies on the exquisite timing of the auditory system, which responds to input more than 1,000 times faster than photoreceptors in the visual system. The axon damage, inflammation, and bruising that result from a concussion can disrupt this microsecond-level temporal precision, leading to poorer encoding of sound.

Using the frequency-following response (FFR), a response to complex sounds originating predominately in the auditory midbrain, we have found auditory processing deficits after a concussion. Specifically, the FFR shows delayed and diminished processing of speech sound details weeks after a sports-related concussion in adolescents with postconcussion syndrome (Kraus et al, 2016) and months to years after recovering from a sports-related concussion in collegiate student-athletes (Kraus et al, 2017). In adolescents with delayed symptom recovery, we see poorer encoding of the fundamental, or lowest, frequency, timing delays of peaks that correspond to the periodicity of the fundamental frequency, and smaller responses (Kraus et al, 2016). The legacy of concussion in the recovered collegiate student-athletes was specific to a reduction in fundamental-frequency encoding (Kraus et al, 2017).

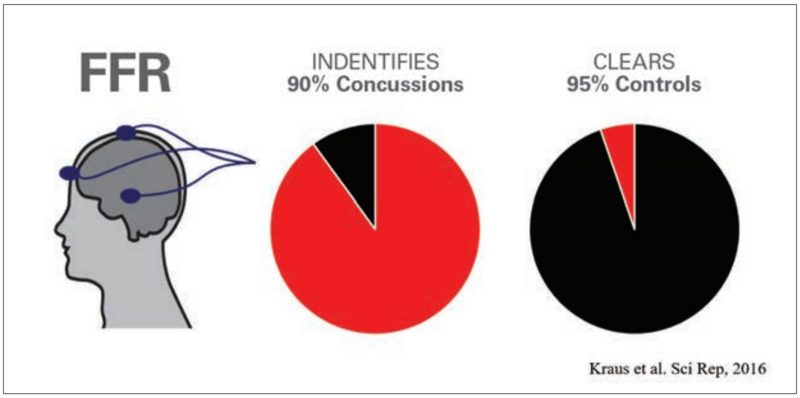
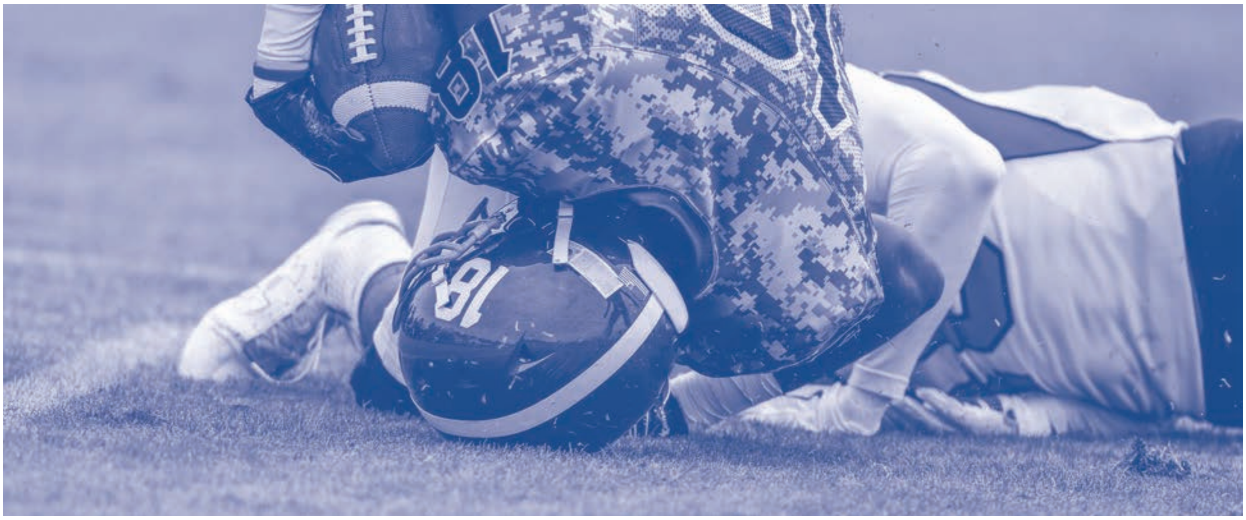


FIGURE 2. Frequency-following response correctly identified 90 percent of the concussed children and cleared 95 percent of the healthy children.

These FFR findings are important for the following two reasons:

(1) In both adolescents with delayed symptom recovery and collegiate student-athletes we observed a poorer response to the fundamental frequency of the speech sound. The fundamental frequency is necessary for conveying pitch, an important cue for perceiving speech in noise. Pitch helps the listener separate the target talker's voice from background noise (Carlyon, 2004). Thus, these findings may hint at reasons for the speech-in-noise difficulties reported postconcussion. In fact, this very measure tracks with speech-in-noise abilities in healthy listeners (Anderson et al, 2010).

(2) In adolescents, we looked at how well the FFR could predict whether the child was concussed. We found that the FFR correctly identified 90 percent of the concussed children and cleared 95 percent of the healthy children (Kraus et al, 2016). The FFR also aligned with symptom severity. Those concussed adolescents with the worst symptoms also had the smallest responses to the fundamental



frequency. And, as the child's symptoms improved, the FFR response recovered, too. (FIGURE 2)

Given the promise of these initial findings, we are continuing this line of research by embarking on a five-year, NIH-funded longitudinal study examining the effects of sports-related concussion and participation in contact and collision sports on auditory processing in male and female collegiate student-athletes.

Applying This Knowledge to the Clinic

Concussions are complex, are sometimes overlooked, and have a broad range of symptoms, which can make concussions difficult to detect and treat. For this reason, concussions must be managed in an interdisciplinary manner. Together with previous research we find that the auditory system is susceptible to damage from a concussion and that this injury can impair listening abilities. Thus, we suggest that audiologists should contribute to this interdisciplinary team. The hearing health of the injured service member or athlete must be considered when treating a concussion. Our hope is that the FFR can provide an objective assessment of auditory brain health that is used in diagnosing and treating concussion.

What Does the Future Hold for Football?

A recent study linking subconcussive hits to CTE in former athletes (Tagge et al, 2018) spurred a call to replace tackle football with flag football for children younger than age 12. Named the Duerson Act, after Chicago Bears legendary football player Dave Duerson, who was diagnosed with CTE following his suicide in 2011, this proposal has gained considerable traction in the Illinois government. It also has fueled a huge debate. For example, a recent editorial by a consortium of sports medicine physicians and researchers has cautioned that the current research does not support ending youth tackle football (Chung et al, 2018).

We must be able to ensure player safety and continue to provide access to sports for children. Playing sports is one of the healthiest things a person can do. It can lead to enhanced mood, physical fitness, social bonding, and a myriad of other positive outcomes. With additional research we can have a better understanding of whether the current risks can be mitigated and if we can make the game we love a safe one.

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Together they research the neurobiology underlying speech and music perception, brain injury, and learning-associated brain plasticity.

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