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Self-Reported Symptoms of Central Auditory Processing Dysfunction Following Mild Traumatic Brain Injury

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Abstract

Mild traumatic brain injury (mTBI), also known as concussion, has emerged as a major public health concern in the United States and worldwide. Of the estimated 1.7 million head injuries that occur nationally each year, about 75% are mTBI. Despite the "mild" label, a significant percentage of these individuals continue to experience a wide array of life-altering physical, emotional, and cognitive post-concussion symptoms for months and years following injury. The central auditory nervous system is vulnerable to several injury mechanisms in TBI and, as a result, auditory problems can be among these long term problems.

Although evidence of auditory processing problems following traumatic brain injury has been reported across a growing number of published case reports and group studies, few studies have investigated the prevalence of such problems due specifically to mTBI. The purpose of this study was to determine whether symptoms consistent with central auditory processing problems were among the persistent post-concussive symptoms seen in those individuals who experience long-term problems. Symptoms of auditory processing dysfunction in a group of mTBI subjects (n = 32) were compared to those reported by un-injured control subjects (n = 27). Participants completed self-reported symptom questionnaires in both auditory and other post-concussion symptom domains. Twelve of the 32 mTBI subjects also completed a mailed follow up including a repeat of the auditory processing questionnaire several months later to evaluate changes in symptoms over time. This same subset also completed an additional hearing disability scale, and results were compared to published data from 1) normal hearing younger and older adults and 2) hearing impaired older adults to investigate how much concussion influenced such symptoms.

Consistent with our hypotheses, individuals with mTBI reported significantly more symptoms of auditory processing difficulty than the age- and gender-matched controls. Some of the highest reported difficulties for mTBI subjects included difficulty listening in background noise, sensitivity to loud sounds, and difficulty understanding rapid speech. Scores from the auditory processing questionnaire were highly correlated with post-concussion symptoms in all the other domains, including depression, fatigue, anxiety, post-traumatic stress, and general concussion symptoms. For the subset of mTBI subjects who completed the auditory processing questionnaire a second time, all of the subjects continued to experience auditory processing symptoms several months to more than two years post-injury. Overall, the mTBI subjects who completed the hearing disability scale had mean scores that indicated more difficulty with speech understanding, spatial location, and perceived quality of speech than did groups of both younger and older normal-hearing adults (without head injury) from published normative studies. Compared to adults with peripheral hearing loss, however, the mTBI group in the current study had slightly better mean scores, consistent with fewer auditory problems. These results suggest that auditory processing difficulties do pose a problem for individuals with mTBI who continue to experience long-term problems after concussion. Further research is needed to determine whether these self-reported symptoms of auditory processing difficulty correlate with performance on central auditory processing tests and/or cognitive tests. This information could lead to better diagnosis and individualized treatment of the long-term problems following mTBI.

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Introduction

Overview

Reports of difficulty hearing in background noise and difficulty following conversations when more than one person is talking are among the most common problems associated with hearing loss. For the majority of individuals who see an audiologist with such symptoms, an audiologic evaluation shows reduced hearing thresholds, which can explain the communication problems they experience. However, for some individuals, the audiogram is “normal”; that is, their problems are not explained by a loss of peripheral hearing acuity. In such cases, the same symptoms may be due to deficiencies in processing auditory information in the central auditory system. Such problems are often called auditory processing problems or disorders.

Although auditory processing problems are most commonly considered to be due to abnormal development of the central auditory nervous system in children, they can also be acquired through disease, degeneration, or injury. Traumatic brain injury (TBI) is one of the mechanisms that may be associated with impaired auditory processing, along with many other physical, cognitive and emotional consequences. Concern over the effects of even mild traumatic brain injury (mTBI), also known as concussion, has grown considerably over the last several years. Evidence of long-term effects of concussions on athletes, including Alzheimer’s-like symptoms and depression, has been widely covered in the media. In the military, mTBI has been labeled the “signature injury” of the wars in Iraq and Afghanistan. Given that mTBI is now widely recognized as a major public health concern in the United States and worldwide, it is of critical interest to identify the types of problems that these individuals experience and determine factors that may predict variability in recovery and best treatment options. The purpose of the current study is to focus on possible central auditory consequences of mTBI.

Background and Review of the Literature

Peripheral vs. central auditory dysfunction

Auditory processing begins in the peripheral portion of the auditory system, which includes the outer, middle, and inner ear, as shown in Figure 1. Sound waves enter the outer ear and cause the tympanic membrane to vibrate, which in turn causes the ossicles of middle ear to move. The mechanical motion of the ossicular chain pushes against a thin membrane of the cochlea (the inner ear). Because the cochlea is fluid-filled, this in and out motion transforms the mechanical energy into hydraulic motion.

The cochlea is a complex structure with three fluid-filled chambers housed in a bony snail-shaped shell. The center chamber holds the organ of Corti, which sits on the basilar membrane along the entire length of the cochlea. There are about 20,000 sensory hair cells along the organ of Corti. Fluid motion in the cochlea causes a shearing motion that bends the fine cilia of these hair cells. This causes the cells to release neurotransmitters to the auditory nerve fibers synapsed to each of the hair cells. The hair cells of the cochlea and the individual auditory nerve fibers are finely tuned to the timing, frequency, and intensity of sounds and this precise information is passed on to be processed at higher levels of the auditory system.

The term "hearing loss" generally refers to problems detecting and recognizing sound due to dysfunction in this peripheral auditory system. There are two main kinds of peripheral hearing loss. A conductive hearing loss is due to damage or blockage in the outer or middle ear and may be temporary or permanent. Sensorineural hearing loss (SNHL) usually refers to damage to the hair cells in the cochlea and is typically a permanent loss. SNHL may also include losses due to damage or degeneration at the synapse between the hair cells and auditory nerve. Common causes of sensorineural hearing loss include age-related degeneration, noise exposure, and ototoxic medications.

Peripheral hearing loss is diagnosed by an audiologist who performs a series of tests to determine at what level of sound in decibels (dB) a person can detect tones at different frequencies in hertz (Hz) important for speech, which are graphed on an audiogram. For adults, a hearing loss is considered to exist when thresholds for detection exceed 25 dB HL on the audiogram, and higher numbers indicate poorer thresholds and more severe hearing loss. In general, as the severity of hearing loss increases from mild to severe, more difficulty understanding speech, especially in challenging listening situations, is experienced. Individuals with SNHL typically experience more difficulty than those with conductive loss, due to loss of sound clarity in addition to the loss of ability to hear softer sounds. Hearing aids are the most common treatment for SNHL.

The central auditory system begins with the auditory nerve (cranial nerve VIII) and includes auditory-specific pathways through the brainstem, midbrain, and cortex, as summarized in Figure 2. The right and left auditory nerves carry the neural signal to the right and left auditory brainstem, where they synapse at the first level of processing, the cochlear nuclei. After the cochlear nuclei, the next major relay station is the superior olivary complex, the first to receive auditory input from both left and right pathways. Both the cochlear nuclei and the superior olivary complex preserve and enhance the fine timing, intensity and frequency information passed on from the eighth nerve and they have important roles in localization and other binaural functions, such as the ability to hear speech in background noise.

Many of the neurons project from the superior olivary complex in a pathway called the lateral lemniscus, to the inferior colliculus, which is the major nucleus of the midbrain. The inferior colliculus plays a critical role in processing binaural information as well as frequency and timing of sound. Beyond the inferior colliculus, the pathway continues to the way station between the brainstem and the cortex, the medial geniculate body, an auditory nucleus on the interior surface of the thalamus. From there, neurons project to the two main auditory areas of the cortex: the primary auditory cortex and the auditory association cortex. The primary auditory cortex is located in the temporal lobe within the Sylvian fissure. The primary auditory cortex is tonotopically organized by frequency like the auditory nerve fibers where the signal originated. Precise processing of timing, amplitude, and frequency cues - which are required for finegrained discrimination of acoustic signals, such as discriminating between consonants - takes place at the cortex.

The auditory cortices in the left and right hemisphere have different functions. Processing in the right primary auditory cortex is critical for syllable pattern detection, pitch perception, dichotic listening, and other non-linguistic information. The left hemisphere is dominant for language processing, including speech perception of specific phonemes. The two hemispheres are connected by the corpus callosum, which allows the auditory cortices to communicate.

Damage within the central auditory system beyond the cochlea may be suspected if an individual reports significant problems understanding speech, especially in noise or other challenging environments, yet the audiogram shows little or no peripheral hearing loss. In general, dysfunction due to damage within the central auditory system causes problems that are referred to not as hearing loss, but as auditory processing problems or dysfunction. In some cases, a central auditory processing disorder (CAPD) may be diagnosed.

Disorders of central auditory processing have to do with the ability to discriminate, recognize, and comprehend auditory information – most importantly speech. That is, central auditory processing ability refers to how efficiently and effectively the central auditory nervous system uses auditory information once it is detected. Auditory abilities such as sound localization, auditory discrimination, auditory pattern recognition, temporal aspects of hearing, and auditory performance with competing and degraded acoustic signals are all considered to comprise central auditory processing (American Speech-Language-Hearing

Association, 1996). The American Speech-Language Hearing Association (ASHA) defines CAPD as difficulties in the perceptual processing of auditory information in the central auditory system as demonstrated by poor performance in one or more of these defined central auditory processing skills (American Speech-Language-Hearing Association, 2005). Some of the commonly reported behavioral symptoms or problems associated with those diagnosed with CAPD are (Whitelaw, 2008):

- Lack of music appreciation
- Difficulty following conversation on the telephone
- Difficulty following directions
- Difficulty following long conversations
- Difficulty taking notes
- Difficulty learning a foreign language or technical information where language is novel or unfamiliar
- Social issues—difficulty "reading" others/pragmatic communication issues
- Spelling, reading, writing issues
- Organizational problems

Identification and treatment of central auditory processing problems

If an individual has symptoms such as described above and yet their audiogram is normal, further evaluation would be appropriate to determine if the problem is related to central auditory processing. Diagnosis of actual CAPD requires a comprehensive case history and diagnostic test battery approach. .

Using appropriate clinical guidelines (American Speech-Language-Hearing Association, 2005), audiologists currently use a battery of behavioral and sometimes electrophysiological test measures to identify whether an individual shows signs of abnormal auditory processing on various skills that reflect processing at different levels/regions of the central auditory system. Depending on the pattern of test results, individualized rehabilitation may involve direct skills training (e.g., retraining the brain to process auditory stimuli by using bottom-up activities and focusing on isolated sounds.), compensatory strategies (e.g., metacognitive and problem-solving skills to improve memory and attention when listening), and environmental modifications (e.g., hearing assistive technology to enhance the clarity of the signal in difficult listening situations), or other accommodations.

Using the label "CAPD" is controversial in the head injury population because of the wide range of deficits including attention, memory, language, self-monitoring, and psychological issues (Musiek & Chermak, 2008). According to some experts, this wide range of processing problems may preclude a diagnosis of CAPD, which they feel only refers to deficits that are *specific* to the auditory modality (Bellis, 2003; McFarland & Cacace, 1995). A wider view is that auditory processing disorders may *coexist* with cognitive top-down disorders, such as attention deficit hyperactivity disorder (ADHD), language impairment, or learning disabilities, but not be caused by them (American Speech-Language-Hearing Association, 2005). Regardless, cognitive processing problems may certainly manifest themselves in problems with auditory tasks (i.e., as listening problems) in a top-down manner.

For the purposes of this paper, symptoms of auditory processing problems, or dysfunction, will be discussed considering the possible influences of damage within the central auditory system as well as the contribution of top-down cognitive processing that manifests in difficulty with auditory information. Specifically, this study investigates symptomology that may be consistent with auditory processing problems in a population with mTBI, but does not propose that a label of CAPD is appropriate in this population. The presence of such symptoms in a significant number of individuals with mTBI would indicate that further evaluation, including use of a battery of behavioral and sometimes electrophysiological test measures to identify whether an individual shows signs of abnormal auditory processing, would be beneficial in this population. Such evaluation would be used to better determine the nature and degree of dysfunction and whether auditory-based intervention may be a valuable addition to the rehabilitation program in individuals with on-going post-concussion problems.

Mechanisms of injury to the central auditory system in MTBI

Approximately 1.7 million Americans sustain a TBI annually (Faul, Xu, Wald, & Coronado, 2010). Of those people who suffer TBI, 52,000 die, 275,000 are hospitalized, and 1.365 million receive treatment and are released from an emergency department – all of which cost the nation $17 billion per year (Centers for Disease Control and Prevention, 2003; Faul, Xu, Wald, & Coronado, 2010). The most prevalent causes of TBI include falls (35.2%), motor vehicle accidents

(17.3%), and being struck by an object (16.5%) (Faul, Xu, Wald, & Coronado, 2010).

TBI can be classified as mild, moderate or severe based on the degree to which the clinical signs above are experienced or noted (Decuypere & Klimo, 2012). One important index, the Glasgow Coma Scale, is a rating scale from 3 to 15 of eye-opening, verbal, and motor function following head injury used to describe an individual's level of consciousness. Brain injury is usually classified using this scale as severe (score 3-8), moderate (score 9-12), or mild (score13-15). Severe TBI is also consistent with loss of consciousness (LOC) lasting more than 24 hours, and post-traumatic amnesia (PTA) for more than seven days, and abnormal findings on neuroimaging exams, such as skull fractures or intracranial hemorrhage. The mortality rate for adults who sustain severe TBI is higher (60%) than it is for children (20%) (Decuypere & Klimo, 2012). A moderate TBI would be diagnosed in cases of LOC lasting between 30 minutes and 24 hours, and PTA lasting for 1-7 days. Moderate TBI patients have the most variability in the clinical presentation, with some requiring intensive care unit hospitalization and others not hospitalized at all. Patients with moderate TBI also have positive neuroimaging findings and can experience a broad range of symptom severity and recovery time.

The vast majority (75%) of TBI cases are mild TBI, making up around 1,275,000 incidents of the 1.7 million cases per year (Centers for Disease Control and Prevention, 2003). Concussion and mTBI are terms that can be used interchangeably. While the term mTBI has generally replaced it in the medical literature, concussion is still a commonly used term in sports. The true number of incidents of mTBI is probably much higher than CDC estimates considering that many concussions go undiagnosed. Many individuals may not realize the significance of such an event, may not seek medical care at the time of the injury, and/or may not follow-up after emergency department visits.

Another reason that true rates of mTBI are likely to be underestimated is that diagnosis can be difficult and there is no standard definition for either mTBI or mTBI-related impairments and disabilities. Using the most widely used definition from the American Congress of Rehabilitation Medicine (American Congress of Rehabilitation Medicine, 1993), mTBI occurs when an impact or forceful motion of the head results in post-traumatic amnesia not exceeding 24 hours, loss of consciousness not exceeding 30 minutes, and a Glasgow Coma Score rating between 13-15. Unless an event is witnessed, however, an individual may not know how long they were unconscious or whether alteration of consciousness occurred. Current neuroimaging tests results are normal in mTBI, with no signs of fracture, hemorrhaging, or other abnormalities. With no major physical indicators, mTBI has been identified as a “silent epidemic” because those affected appear fine on the outside.

There is a wide range of possible consequences of mTBI. There can be short-term changes to a person’s cognitive health (attention, memory, concentration), emotional health (depression, anxiety, irritability), and physical health (dizziness, sleep disturbance, headache). For the majority of people, these symptoms generally resolve within the first three months following injury, many within the first days/weeks. Because of this, it has commonly been thought that concussions were minor injuries with short-term consequences. It is now estimated, however, that a significant number (15% to > 30%) of mTBI patients experience persistent symptoms beyond the first six months (Bohnen, Jolles, & Verhey, 1993; Ingebrigtsen, Waterloo, Marup-Jensen, Attner, & Romner, 1998; Ponsford et al., 2000; Rimel, Giordani, Barth, Boll, & Jane, 1981; Vanderploeg, Curtiss, Luis, & Salazar, 2007; Wood, 2004). Individuals who experience such chronic, persistent symptoms are often referred to as having post-concussion syndrome. Some of the most commonly reported long-term problems include physical symptoms such as headache, dizziness, sleep problems; psychological symptoms such as depressed mood, irritability, anxiety, memory, concentration, and executive function; and sensory problems, including sensitivity to visual and auditory information. Such symptoms can greatly impact daily life and the ability to carry out regular activities, including work and school. Some researchers have reported unemployment rates of 34% at three months following mTBI and 9% still unemployed a year after injury (Guthkelch, 1980; Rimel, Giordani, Barth, & Jane, 1982). Concussion and post-concussion syndrome, therefore, can have major effects on a person's quality of life for a long time following a "minor" head injury. Because mTBIs are estimated to cost the nation nearly $17 billion each year, they represent a major public health concern (Thurman, 2001). Better knowledge of the symptoms that indicate concussion and post-concussion syndrome, therefore, may be useful in helping professionals and the public to identify and treat these problems more quickly.

Symptoms that could play a larger role in awareness and treatment for concussion are those related to the auditory system and auditory information processing. Damage to the peripheral auditory system including the external, middle, and inner ear can occur in head injury, particularly if the temporal bone receives direct impact or in a blast or explosion. While such damage may cause conductive or sensory hearing loss, peripheral hearing loss is relatively uncommon in mTBI compared to more moderate or severe injuries or blast-injuries (Barber, 1969; Belanger et al., 2011; Munjal, Panda, & Pathak, 2010). Therefore, while peripheral hearing should always be evaluated, it is not likely to be the cause of the auditory problems reported following mTBI. Tinnitus (ringing or sounds in the ears) and dizziness, however, are extremely common following mTBI and are part of commonly recognized post-concussion symptoms. Both tinnitus and dizziness can be peripherally or centrally based and it may be difficult, or impossible, to determine the cause. Regardless, both of these common symptoms are areas where audiologists and other professionals can provide rehabilitative services.

The entire central auditory pathway may be vulnerable to both direct and indirect mechanisms of injury following head injury. The direct mechanism of injury from impact forces can cause contusions, hematomas, and lacerations in that specific location (although these are not typically detected by imaging in mTBI), as well as more diffuse damage. This includes damage from acceleration and deceleration forces of the brain as it moves back and forth in the fluid environment and impacts against the skull, as well as diffuse injury to neurons caused by stretching and shearing forces. Following these initial impact events, there is swelling, lack of oxygen, and delayed axonal degeneration that cause widespread neuronal changes throughout the central nervous system, including structures of the central auditory system, and this damage may not be detected with current imaging and medical assessment procedures.

The eighth nerve and auditory brainstem nuclei may be particularly susceptible to the effects of the forceful rotation movements in acceleration-deceleration forces as well as the general axonal degeneration that follows (Gennarelli & Graham, 1998). The primary auditory cortex, which is located on the surface of the temporal lobe, may be particularly vulnerable to injury from brain impact against bony ridges of the sphenoid and temporal bones (Gutierrez-Cadavid, 2005). Current imaging and diagnostic techniques are not sensitive enough to identify all damaged structures within the auditory system, although animal models have confirmed such damage to the auditory pathway does occur in induced TBI (Danielidis et al., 2007; Makishima & Snow, 1975). In addition, difficulty understanding auditory information could be caused by damage to brain structures in the vulnerable frontal lobes and portions of the temporal lobes involved in cognition, memory, and attention.

In sum, although the brain injury may be classified as “mild” TBI, the effects can still be serious and life-altering, with persistent long-term problems or post-concussion syndrome. Auditory processing problems could be among these long-term symptoms due to the vulnerability of the entire auditory pathway through the direct and indirect mechanisms of injury. It is important, therefore, to establish how common auditory processing problems are following mTBI and how these auditory symptoms fit within the spectrum of post-concussion problems experienced by thousands of individuals each year.

Literature review of concussion and auditory processing problems

The literature on the auditory consequences of head injury, specifically, mTBI, is limited but growing. A number of published case reports and studies support that central auditory processing problems may be among the problems experienced by a significant number of individuals after TBI. One of the problems in the early literature, however, is that the severity of TBI is often not well specified, if discussed at all. Another limitation is that the studies are not well controlled in terms of classification of the timing, severity, and number of injuries, or in the definition or classification of auditory processing problems. Many of the publications are case studies, rather than larger studies comparing TBI and control groups. These factors make it difficult to draw specific conclusions about the presence of auditory processing problems in mTBI, but provide initial evidence for increasing awareness of possible central auditory dysfunction in this population.

Evidence of central auditory processing dysfunction resulting from head injury has been published in a number of case reports with single or a few subjects. In one of the earliest of these case reports linking central auditory processing dysfunction to head injury, Hall et al. (1983) discussed data from three individuals who had suffered TBI. Two out of three subjects followed in this study were found to have evidence of abnormal auditory processing by evoked potential and behavioral tests 3-10 months after injury. These three cases were all severe TBI.

A more recent case report (Fligor, Cox, & Nesathurai, 2002) demonstrated long-term auditory deficits can persist in TBI cases that were not revealed by a standard hearing test. The authors described the case of a woman with reported auditory difficulties 13 years after head injury. The hospital records from the time of injury showed evidence of hemorrhage and brain contusion on the CT scan. She reported such problems as difficulty with sound quality and understanding conversation, particularly in challenging situations such as background noise or with accented speech. Word recognition testing showed some abnormal findings, including reduced understanding of speech at higher vs. lower intensity levels, which are findings consistent with central auditory pathologies.

Another recent case report provided not only evidence of abnormal auditory function following a head injury, but evidence that direct auditory training may provide benefits in rehabilitation. Murphy et al. (2011) conducted standard audiological tests, including audiometry, immittance measures, auditory evoked potentials and behavioral tests of central auditory processing in an adult 12 years following traumatic brain injury. Although the injury was not specified as mild, moderate, or severe, a Glasgow Coma Scale score of 12 was reported, which would indicate a moderate TBI according to the ACRM definition. The authors concluded from the diagnostic test results that the man had a moderate auditory processing disorder including deficits in the ability to attend to auditory information in background noise, the ability to identify temporal patterns, and verbal memory. An auditory-based training was prescribed for rehabilitation. After eight sessions of auditory training, the subject showed improvement in both the behavioral and objective measures of central auditory processing. The subject also improved in 5 of out 7 cognitive abilities following auditory training. The authors interpreted this result as an influence of auditory training on cognitive, top-down abilities.

There have been a few larger studies that looked at the prevalence and nature of central auditory processing problems in groups of individuals with traumatic brain injury compared to control groups. Bergman, Hirsch, and Solzi (1987) reported significant findings in a group of individuals following head injury using behavioral tests of central auditory function, such as sentence understanding in competing noise. The severity of head injury was not specified in this study, nor was the time period between the injury and auditory testing. The authors stated that the “vast majority” of head injury subjects had normal peripheral hearing. Forty-three percent of the subjects were found to have abnormal results on the competing sentences test. In a second experiment, head injury and healthy subjects with hearing no worse than a mild hearing loss completed similar tests of speech recognition in the presence of competing sentences. Overall, the performance scores for the head injury group were at least two standard deviations below those of the controls (Bergman, Hirsch, & Solzi, 1987).

Several studies since 1992 have suggested that a significant proportion of those who sustain TBI of varying severities have central auditory dysfunction.

Cockrell and Gregory (1992) performed a retrospective study looking at 62 cases of pediatric TBI to determine the prevalence of peripheral and central auditory deficits. The severity of TBI in the study ranged from mild to severe as indicated by reported Glasgow Coma scores ranging from 3 to 13. There is no indication of the time between injury and auditory testing. All subjects completed standard audiometric evaluations. If central auditory problems were suspected in individual subjects, behavioral central auditory testing was also completed, either a test of auditory processing for patients aged 3-10 years or a competing sentences test and dichotic listening test for those over 10 years of age. Based on the outcomes of these tests, the prevalence of central auditory processing problems was reported to be 16% (Cockrell & Gregory, 1992).

A higher percentage of central auditory processing deficits was observed by Bergermalm and Lyxell (2005). The study included 47 total subjects (both TBI and control) ranging in age from 16 to 60 years. TBI subjects were tested 7-11 years after injury. Because skull fracture and/or brain contusion were identified by CT scan, this group would likely be classified as moderate to severe TBI. The participants are also described as "well recovered" at the time of testing. Central auditory tests included auditory brain stem response (ABR), an objective test that evaluates the central auditory system including the eighth cranial nerve and brainstem levels; and behavioral tests of distorted speech recognition and phase audiometry (which test localization skills). Of the 22 TBI subjects, 11 demonstrated ABR deficits (50%). Of those participants who had ABR deficits or abnormal behavioral audiometric results, 80% of them also had poor cognitive performance scores (Bergermalm & Lyxell, 2005).

Another study (Jury & Flynn, 2001), including 30 participants aged 21-45 years who suffered TBI in the last 19 months to 27 years, investigated auditory and vestibular problems post-TBI. The severity of TBI was not indicated; however, across the 30 participants, length of post-traumatic amnesia ranged from none to 5.5 months, indicating that TBI from mild to severe may have been included. The results showed high incidence of tinnitus (53%), vestibular difficulties (83%), and hyperacusis (sensitivity to specific loud sound) (87%) following TBI, which could be consistent with central auditory damage.

All of the above studies included either primarily severe TBI cases or mixed severities. Few studies have specifically looked at the prevalence of central auditory processing problems following mTBI or concussion. A recent case specific to mTBI was published reporting the experience of a woman who sustained a concussion after being thrown from a horse and landing on her head (Baran, Musiek, & Shinn, 2004). Peripheral and central auditory tests were conducted 13 months after the injury and another seven months later post-therapy. The central auditory tests included the following electrophysiological and behavioral tests: middle latency response (MLR, a neural response generated at the midbrain/cortex), dichotic digit recognition (pairs of digits presented to each ear at the same time), frequency and duration pattern recognition, time-compressed (rapid) speech, and competing sentences. Pre-therapy scores for competing sentences, dichotic digits, duration pattern recognition and compressed speech tests were all abnormal compared to normative data. Frequency pattern recognition and MLR results were found to be within normal limits. The authors interpreted the results as evidence of central auditory processing deficits due to concussion (Baran, Musiek, & Shinn, 2004). In support of this conclusion, improvements were seen in understanding of competing sentences and dichotic digits following the period of dichotic interaural intensity difference training.

Another recent study examined auditory processing *specifically* in individuals with concussion/mTBI (Turgeon, Champoux, Lepore, Leclerc, & Ellemberg, 2011). The study included a group of 16 male sports athletes, 8 with a history of documented concussion and 8 who had no history of concussion. The concussions were all sustained 3-10 years before peripheral and central auditory tests were completed. Behavioral central auditory processing tests included tone-pattern recognition, speech recognition in a background of competing speech, and dichotic listening abilities. The results showed normal peripheral auditory abilities for all participants and normal central auditory processes for all of the non-concussed subjects. The mean scores on the central auditory tests for the concussed athletes fell two standard deviations below the average scores of the non-concussed athletes. Five out of the eight concussed athletes showed deficits in one or more central auditory processing tests. These results provide initial evidence that even mTBI can result in central auditory processing problems. However, limitations include the variability in the number of concussions (1-5), the time since the last concussions (3-10 years), and the small number of subjects.

Additional evidence of abnormal auditory processing following mTBI has been provided by a relatively large study in the military veteran population. Gallun and colleagues (2012) investigated effects of blast-related injuries on the central auditory system. Blast-injuries are unique to explosion events where a force (blast wave) creates great pressure on the body, which can cause an array of injuries, such as ruptured tympanic membrane (ear drum), pulmonary damage, and toxic exposures. They are often accompanied by head injury, especially mTBI. Additional auditory deficits in blast-related injury (with and without mTBI) include peripheral hearing loss, tinnitus, and bleeding from the ear canal. Of the 36 total blast-exposed subjects studied, 19 were diagnosed with mTBI. Participants were required not to have more than a moderate peripheral hearing loss and generally, most subjects had no worse than a mild loss. Behavioral tests, including temporal pattern perception, auditory temporal resolution, binaural processing and sound localization, and dichotic listening were completed in 36 blast-exposed patients and age- and gender-matched controls. The results on the behavioral tests revealed that 75% of the blast-exposed patients had abnormal results on at least one of the tests. The greatest differences between blast-exposed and control groups were observed in the tests pertaining to gap detection in noise (temporal processing) and dichotic word recognition. Overall, there was a statistically significant difference between the blast-exposed mTBI patients and the control subjects on tests of central auditory processing. While these findings are not specific to mTBI alone, they may be consistent with the idea that both blast-related and non-blast related mTBI can have similar effects on central auditory processing.

In sum, this literature review highlights studies that reported on the relationship between TBI and auditory processing dysfunction. While central auditory processing deficits have been reported in individuals following traumatic brain injury of all severities (but especially severe TBI) at rates of 16%-50%, there have been few studies including or specific to the mTBI population. The limited evidence currently suggests that auditory processing problems may be a common part of post-concussive problems in this mTBI population (from 50%-75% in two studies).

Purpose of Study

This study was designed to address several research questions. These questions addressed: 1) the prevalence of auditory processing problems in a group of individuals experiencing continued post-concussion symptoms following mTBI; 2) how auditory problems related to specific known post-concussion symptoms, such as depression, anxiety, and fatigue; 3) whether self-reported improvement or decline in symptoms related to auditory processing was observed over time; and 4) the utility of a questionnaire geared towards hearing aid benefit in providing information about the nature of the auditory-based symptoms experienced by individuals with mTBI. The results of this study may help audiologists and other professionals better serve the needs of patients who have experienced mTBI, which represents a major public health concern. These findings may contribute to our understanding of the need for referral to audiologists, diagnostic testing and possible auditory-based intervention for individuals experiencing post-concussion syndrome. In addition, this study could provide incentive for future research to expand the knowledge base relative to the role of central auditory processing among post-concussion problems and factors that may predict severity of symptoms and the timeline of recovery. Such research could eventually lead to better diagnosis and rehabilitation of not only auditory, but perhaps also to a wider range of post-concussion problems.

Methods

Subjects

Thirty-two subjects with concussion and 27 subjects without concussion (controls) participated in this study. The experimental participants were recruited from State University of New York (SUNY) Upstate Medical University outpatient Brain Injury and Concussion Management Programs. All the participants in this group were diagnosed with mTBI by professionals at SUNY using the American Congress of Rehabilitation Medicine (ACRM) definition. The concussed subjects consisted of 10 males and 22 females ranging in age from 18-60 years (mean age 42.3). All subjects were a minimum of three months and a maximum of 18 months post-injury, and none of the subjects had previously diagnosed concussion prior to the current injury. The primary injury mechanisms for this group of subjects were road/traffic accident (37.5%), hitting the head on a stationary object (22%), falls (18.75%), being struck by an object (15.6%), and violence/assault (6.25%). Because they continued to have symptoms that lead them to be enrolled in rehabilitation, all of the mTBI subjects would be considered to have post-concussion syndrome.

In addition, a group of age- and gender-matched control subjects were recruited from Syracuse University and the local community. The control subjects consisted of 6 males and 21 females ranging in age from 18-60 years (mean age 42.2). All participants were native English speakers and had no previous history (pre-concussion) of diagnosed, learning, neurological, or psychological problems. All participants provided written informed consent as approved by the institutional review board of Syracuse University and SUNY Upstate Medical University.

General Procedures

Pure tone threshold testing was completed for the frequencies of 250 Hz to 8000 Hz. All participants were required to have hearing thresholds of 40 dB HL or better for frequencies up to 4000 Hz, indicating no more than a mild hearing loss. Mean audiometric thresholds for both the mTBI and control groups are shown in Figure 3. There were no statistically significant differences in pure tone thresholds between groups except at 250 Hz in the left ear ($p = .023$). Although this comparison reached statistical significance, the mean for both groups was well within normal limits and the 3 dB difference would not be considered clinically significant.

Following completion of hearing testing, each participant completed case history and background questions about hearing health, injury information, and demographics. At the time of enrollment, all subjects completed all of the study questionnaires described below including the auditory processing symptoms (APS) questionnaire and several additional post-concussion symptom questionnaires.

In addition, follow-up questionnaires were sent by mail to the mTBI subjects to evaluate changes in auditory symptoms over time. The APS and an additional questionnaire called the Speech, Spatial, and Qualities of Hearing Scale (SSQ) were mailed to all mTBI participants at least 3 months after their initial enrollment. A subset of 12 mTBI subjects mailed the questionnaires back in pre-stamped envelopes.

Questionnaires

The outcome measures used in this study were self-reported auditory, cognitive, and neuropsychological symptoms associated with mTBI. The questionnaires used in this study, which are described in detail below, included two measures of self-reported auditory symptoms and five measures of other physical, emotional, and cognitive post-concussion symptoms.

Auditory processing symptoms questionnaire

A set of 12 questions was used for this study to assess common symptoms related to auditory processing dysfunction, modified for adults from published questionnaires, such as the Fisher's Auditory Checklist (Fisher, 1985) and the Scale of Auditory Behaviors (Schow, Seikel, Brockett, & Whitaker, 2007). For the purposes of this study, we refer to this set of questions as the auditory processing symptoms (APS) questionnaire; however, this is not a published questionnaire and has no associated normative data. Participants were asked to rate each item on the APS, based on symptoms they experienced within the last two weeks, as “Yes”, indicating they experienced the symptom frequently/all the time; “Sometimes”, indicating they experienced the symptom occasionally; or “No”, indicating rarely or never. Two points were assigned to each “yes”, 1 point for “sometimes”, and 0 points for “no” so that the total score was 0 if none of the symptoms were experienced and increased to a maximum of 24 if all symptoms were experienced frequently (i.e. higher scores indicate more perceived auditory processing problems). A copy of the APS is included in Appendix A.

The APS was administered to all subjects at the time of their enrollment in the study. In addition, a second copy of the APS was sent in the mail to the mTBI subjects 4-25 months later to evaluate whether reported symptoms related to auditory processing improved, worsened, or stayed the same in the time period following the study. For the remainder of the document, scores for the initial APS completed at enrollment are labeled as APS1 and the second scores completed at follow-up are labeled as APS2.

The Speech, Spatial, and Qualities of Hearing Scales (SSQ)

This hearing disabilities questionnaire was created by Gatehouse and Noble (2004) to assess the benefit and efficacy of hearing aids by having participants complete this questionnaire before and after trying hearing aids. Recent studies have shown that the SSQ may be sensitive not only to perceived disability due to peripheral hearing loss, but also to auditory disabilities due to changes in the central auditory system due to factors such as aging (Banh et al.

2012). The questionnaire is divided into three sub-sections: speech hearing, spatial hearing, and qualities of hearing. The speech hearing section asks about the participants' ability to hear and understand speech in a variety of difficult listening situations, including listening in background noise and listening when multiple people are talking. The second section on spatial hearing asks about perceived difficulty hearing in different environments and determining the spatial location of a sound source. The third section of the SSQ focuses on listening effort, recognition of sounds, and the clarity of sounds.

Each question is answered using a scale from 0-10 with 0 showing inability to hear or understand in the situation described and 10 showing perfect ability to hear or understand in the described situation. Therefore, high scores on the SSQ indicate fewer perceived problems hearing and listening, and low scores indicate considerable difficulty. The SSQ (version 5.6) was part of the mailed follow-up study and was completed by the subset of subjects in the mTBI group 4-25 months after initial enrollment to evaluate whether this measure may be sensitive to problems experienced by individuals with post-concussion syndrome and its relationship to the results on the shorter survey, the APS.

Beck Depression Inventory II (BDI-II)

The BDI (Beck, Steer, & Brown, 1996) is a self-report inventory of depression symptoms experienced over the past two weeks using 21 questions. Each item consists of four statements increasing in severity for the specific symptom, such as sadness, self-dislike, and loss of pleasure. The participant circles one of the four statements numbered 0, 1, 2, or 3, which describe an increase in the severity of the symptom. For example, the first item is “sadness” and the person would circle “0: I do not feel sad at all”, “1: I feel sad much of the time”, “2: I am sad all the time”, or “3: I am so sad or unhappy I can’t stand it”. The total score is calculated by adding up the circled numbers for all 21 questions with a possible range from 0 (indicating that no symptoms were experienced) to 63 (indicating all symptoms were experienced to their fullest). Scores on the BDI-II are generally interpreted clinically within the following ranges: 0–13 minimal depression; 14–19 mild depression; 20–28 moderate depression; and 29–63: severe depression.

Beck Anxiety Inventory (BAI)

The BAI (Beck & Steer, 1990) is a self-report questionnaire of symptoms of anxiety experienced during the past month. There are 21 items with symptoms of anxiety, such as feeling hot, unsteady, difficulty breathing, and scared. Each item is rated from 0 (not at all) to 3 (severely – it bothered me a lot). The total score is calculated by summing all the columns together. A total score of 0 represents that no symptoms were experienced and a score of 63 represents that all symptoms were experienced to the fullest. Typically, the test is interpreted clinically using the following cutoffs: 0-7 minimal level of anxiety; 8-15 mild anxiety; 16-25 moderate anxiety; and 26-63 severe anxiety.

Fatigue Severity Scale (FSS)

The FSS (Krupp, LaRocca, Muir-Nash, & Steinberg, 1989) questionnaire assesses the severity of fatigue symptoms through self-reporting. There are nine items concerning how fatigue affects motivation, exercise, physical functioning, carrying out duties, interfering with work, family, or social life. Each statement is rated from 1 (strongly disagree) to 7 (strongly agree) based on how much the symptom relates to the individual in the past week. A mean score is calculated for the 9 questions so that the range of scores is 1-7. Scores of 4 or more are generally interpreted as indicating high fatigue in clinical populations.

Rivermead Post-Concussion Symptoms Questionnaire (RPQ)

The RPQ (King, Crawford, Wenden, Moss, & Wade, 1995) is a self-report questionnaire of symptoms commonly experienced after a concussion in comparison to how prevalent those symptoms were before concussion. Symptoms such as headaches, dizziness, noise sensitivity, irritability, and poor concentration are assessed. Participants are asked to rate current symptoms (within the last 24 hours), using their pre-injury experiences (if applicable) as a baseline comparison. The 16 items are rated from 0 (not experienced) to 4 (severe problem). In the modified version of scoring, the physical symptoms of the first 3 items (headache, nausea, and dizziness) are added together to obtain the RPQ3 score (0-12 possible) and the total for the last 13 are added together separately to obtain the RPQ13 score (0-52 possible).

PTSD CheckList – Civilian Version (PCL-C)

The PCL-C (Weathers, Litz, Herman, Huska, & Keane, 1993) is a 17-item questionnaire which asks about symptoms in relation to "stressful experiences" within the past month. Originally developed for the military, the civilian version can be used in any population exposed to traumatic events. The items are based on the DSM-IV symptoms of Post-Traumatic Stress Disorder (PTSD). The 17 items are rated in terms of how much the individual has been bothered by each one on a 5-point scale ranging from 1 (“not at all”) to 5 (“extremely”). A total symptom severity score (range = 17-85) can be obtained by summing the scores from each of the 17 items. Scores of 50 or greater are typically interpreted as possible PTSD.

Data Analysis

All of the published questionnaires provided guidelines for scoring the items and summing the totals. One-way ANOVA tests were used to compare mean scores by group. The linear relationship between scores across different questionnaires and by individual question pairs was evaluated using Pearson’s correlation analyses. Repeated measures ANOVA testing was used when analyzing performance on the first and second trials of the APS.

Results

Symptoms of auditory processing dysfunction at the initial visit

The main measure of auditory processing problems in the current study was the APS questionnaire, which was administered at the time of enrollment (APS1) in the study to all subjects, with and without concussion. As seen in Figure 4, the mTBI group reported a much higher rate of auditory processing problems overall with a mean score of 13.3 (s.d. 4.5), where the maximum score of 24 indicated that all symptoms were frequently experienced. By comparison, the mean overall score for the age- and gender-matched controls was only 1.9 (s.d. 2.1), which was a statistically significant difference ($F = 132.314$, $df = 1$, $p < 0.001$).

Figure 5 shows the average score per question on the APS1 for each group, where each question was scored from 0-2 (0 being “no”, 1 being “sometimes”, and 2 being “yes”). The mTBI group scored higher than the control group on every question and had an average score greater than 1 for 7 out of the 12 questions, indicating that the majority of symptoms were experienced sometimes or all the time. By comparison, none of the control group individual question averages exceeded 0.5. The between-group difference in scores was statistically significant ($p \leq 0.002$) for all 12 questions, indicating that mTBI subjects reported experiencing a higher rate of for all the listed symptoms related to auditory processing problems.

The five APS items that received the highest scores (1, 3, 6, 10, 11), indicating the most reported difficulty, were further reviewed for both mTBI and control subjects as shown in Figure 6. Item 1 states: “I have problems hearing and/or understanding in background noise or reverberation (echo/poor acoustics)”. More than 50% of the mTBI group answered “yes” and 38% reported “sometimes” while none of the control group subjects answered “yes” to this question, and 21% answered “sometimes”. Item 3, which asks about trouble understanding rapid or muffled speech, shows similar percentages for the mTBI subjects as item 1.

Item 6, which asks about increased sensitivity to loud sounds, had the highest percentage of mTBI subjects answering “yes”, at 72% indicating that this was a very common problem for the group. Although it was not a problem for 63% of the control group, three of the control subjects reported “yes” to item 6 and eight reported “sometimes”. Problems paying attention when people talk and difficulty memorizing information learned by listening – items 10 and 11, respectively – show more equal proportions for responses of “sometimes” and “yes”, around 50% in each category for both questions, for the mTBI population. No control subjects reported “yes” to item 10 and only one person reported “yes” to item 11, indicating that these problems were very uncommon in the un-injured population. Overall, mTBI subjects report a high number of symptoms related to auditory processing dysfunction while controls reported experiencing very few in their daily lives.

Correlations between individual pairs of APS questions were evaluated using Pearson correlation analysis to see whether response scores for Question 1, for example, significantly related to those for Question 2, etc. Scores for all question pairs were significantly correlated with each other at a significance level of $p = .05$, except for questions 8 (understanding on the phone) and 9 (difficulty reading and writing) ($p = .061$). The majority of correlations (62 out of 66) were significant at the level of $p = .001$, with r-values ranging from $r = .34$ to .77. Pearson correlation coefficients of $r = 0.50$ or higher were obtained for 34 out of 66 comparisons, indicating that the questions were moderately or strongly correlated with each other. The strongest correlation of $r = 0.77$ was found between questions 1 and 3. That is, the strongest relationship was between problems hearing and/or understanding in noise or reverberation and problems understanding rapid or muffled speech.

Auditory processing problems and other post-concussion symptoms

In addition to the auditory processing problems, other symptoms common in post-concussion syndrome were also evaluated to assess the relationship between reported auditory processing problems and the general post-concussion symptom profile experienced by individuals following mTBI. Correlation analyses were completed to compare total scores on the APS to total scores on each of the other questionnaires given at the same visit. Figure 7 shows that there was a strong positive correlation between APS scores and the scores on each of the other symptom questionnaires. All correlations were significant ($p<0.001$). The highest correlation was found for the APS and the RPQ13 ($r = 0.90$), indicating that the number and severity of reported auditory processing problems were highly correlated with the number and severity of common post-concussion symptoms such as forgetfulness, poor concentration, and irritability. High correlations of $r = 0.80$ and above were also found between the APS and depression (BDI-II, $r = 0.80$), physical post-concussion symptoms such as headaches, dizziness, and nausea (RPQ3, $r = 0.86$), and fatigue scores (FSS, $r = 0.82$). Anxiety (BAI, $r = 0.79$) and PTSD (PCL-C, .0.76) showed slightly lower, though still strong, correlations with reported auditory processing problems. Overall, individuals who reported a high number of auditory symptoms also reported a high number of symptoms across all of the post-concussion symptom domains.

Follow-up questionnaires assessing auditory processing problems

The second part of the study evaluated whether symptoms of auditory processing dysfunction change over time following concussion and how results on the APS symptom questionnaire might relate to a published symptom questionnaire designed for hearing-impaired individuals, the SSQ. Twelve of the mTBI subjects completed and mailed back the APS2 and the SSQ for analysis. Table 1 shows the scores for these questionnaires along with age, gender, and time since injury information for these 12 individuals. The data in this table are sorted by the initial score on the APS1, from lowest (fewest symptoms) to highest (most symptoms).

For half the subjects, scores for the APS1 and APS2 suggested little change in their perception of the severity or frequency of auditory problems (within ±2 points). This can be seen in Figure 8, where many of the points lie along the diagonal line indicating equal scores for the two time periods. Of the remaining half, three subjects showed improvement in scores by of 7 or 8 points (out of 24) and three subjects' scores were worse for APS2 than APS1 by 3-6 points. Repeated measures ANOVA showed that symptoms scores for APS1 and APS2 were not significantly different for the group as a whole ($p= 0.674$). APS1 and APS2 scores were also not significantly correlated for the group ($p= 0.178$, $r = 0.416$).

There was not an identifiable pattern in the time since injury or individual question scores for subjects whose scores improved vs. those whose scores worsened. Of those who showed improvement, all three had similarly high symptom scores (13-14 out of 24) on the initial questionnaire and all three reported perceiving an overall improvement in symptoms. M09 took the APS1 at about 6 months post-injury and completed the APS2 19 months later. M29 had a longer period post-injury (9 months) but completed the APS2 within a shorter time frame (5 months). M31 took the APS1 4.5 months post-injury and completed the APS2 about 4 months later. Overall, M09, M29, and M31 reported improvement in a number of auditory processing problems, but the individual questions with scores indicating improvement were not the same across these subjects. Question 6 about sensitivity to loud sound showed improvement in two of the subjects (M09 and M29).

Of the three participants whose scores reflected an increase in number of self-reported symptoms on the APS2, scores for subjects M23 and M24 both increased by 3. Further, both were 4-6 months post-injury at the initial visit and with about 6 months between the first and second APS questionnaires. Both of these subjects had relatively low initial APS scores (6 out of 24). M24 reported an overall impression that his symptoms had stayed the same while M23 did not answer the question. A third participant, M28, who initially scored slightly higher (11) had a 6-point increase in scores from a time 5 months post-injury to 11 months post-injury, but did not answer the question about overall perception of change. There were no individual questions that were consistently rated as worse across the three subjects.

In summary, the subjects who initially reported lower scores on the APS1 all reported an increase in symptoms when completing the APS2 6-19 months later. In contrast, some of the highest scoring subjects on the APS1 reported a significant decrease in symptoms on the APS2. Those who reported the most symptoms on the APS1 had scores that barely changed by the time they completed the APS2 and their overall perception of symptoms stayed the same.

Speech, Spatial, and Qualities of Hearing Scales

The use of a detailed questionnaire about hearing and auditory symptoms was also investigated in this same sub-group of 12 subjects at the time they completed the APS2. The SSQ asked for ratings of difficulty in hearing and listening in three categories: speech understanding, spatial listening, and quality of auditory information. Each question on the SSQ represents a listening situation and the subject is asked to rate whether he/she can hear or understand in that situation on a scale from 0 (not at all) to 10 (perfectly), therefore *higher* scores on the SSQ represent *fewer* auditory problems.

To evaluate possible relationships between questionnaire items, correlations between APS1 scores and SSQ scores for each subject were analyzed. APS1 scores and scores for the speech hearing items on the SSQ were not significantly correlated ($r = -0.44$, $p= 0.155$). Moderately strong correlations were found between the APS1 and the spatial hearing ($r= -0.66$, $p=0.020$), and qualities of hearing ($r = -0.67$, $p= 0.016$) sections on the SSQ. Overall, there was at least a moderate relationship between symptom scores on the APS and portions of the SSQ.

Because there was no control group for this part of the study, the data collected from these individuals with mTBI was compared to published data from other studies using the SSQ to assess auditory problems. Comparisons were made to scores from populations of younger adults (YA: ages 18 to 22) and older adults (OA: ages 64 to 80) with no or minimal hearing loss from a study investigating auditory effects of aging (Banh, Singh, & Pichora-Fuller, 2012) and to scores from a population of older adults with peripheral hearing loss (HI: mean age 71, s.d. 8.1) (Gatehouse & Noble, 2004). The comparisons for mean SSQ scores across studies are shown graphically in Figure 9 and numerically in Table 2.

As shown in Figure 9, the mean scores for young, normal hearing adults (YA) were the highest across the speech, spatial and quality sections of the SSQ, indicating, as expected, that this group experienced few auditory problems. The OA group with minimal hearing loss had lower mean scores than the YA group across categories, and this difference was significant (Banh, Singh, & Pichora-Fuller, 2012). The HI group had the lowest mean scores across studies, indicating the most auditory-related problems. While the ages of the mTBI subjects in this sub-group (range 24-59) were between the two groups, their mean scores were lower than either the YA or OA groups from Banh et al. (2012) for all three sections of the SSQ. The mTBI group scores were slightly higher than those reported for the HI adults.

To get a better idea of the problems experienced by each group, a comparison of the scores by individual question is shown in Table 2. It should be noted that the exact version of the questionnaire differed slightly across studies. For the spatial hearing items, Banh et al. (2012) did not report scores for question 14 ("Do the sounds of things you are able to hear seem to be inside your head rather than out there in the world?") or questions 16 (hearing as driver in a car) and 17 (hearing as passenger in a car) in the qualities of hearing section. Gatehouse & Noble (2004) had an additional question about hearing aids, which was not included in the version of the questionnaire used in the current study. Items were re-numbered as necessary according to the published descriptions and appear in Table 2 for the version given to the subjects in the current study.

Figure 10 displays the between-group difference in mean scores for each question calculated from the data in Table 2. The difference was calculated by subtracting the mean scores for the mTBI group from each of the other group means. Therefore, positive scores (upward vertical bars in Figure 10) indicate that the mTBI group had a *lower score* for that particular question, consistent with the mTBI subjects having *more reported difficulty* than the comparison group. Conversely, negative scores (downward bars) indicate that the mTBI group *scores were higher*, consistent with *less perceived difficulty* than the comparison group.

As can be observed in Figure 10, the mean symptom scores for YA and OA groups were higher than those of the mTBI subjects from the current study (upward bars) across all individual questions in all three sections. This result suggests that the mTBI subjects perceived more difficulty in speech understanding and spatial listening and decreased quality of auditory information as compared to groups with normal hearing or minimal hearing loss, whether younger or older. Mean scores for HI subjects were generally lower than those of the mTBI group across most individual questions, indicating that the mTBI subjects did not report as much difficulty across these contexts as individuals with peripheral hearing loss.

There were a few questions, however, for which the mTBI subjects' scores were lower than the HI group, suggesting that for a few situations, the mTBI group seemed to report more difficulty even than the HI group. In the spatial section, the mTBI subjects reported more problems on two of the questions (14 and 15). Question 14 asks, "Do the sounds of things you are able to hear seem to be inside your head rather than out there in the world?" Question 15 asks, "Do the sounds of people or things you hear, but cannot see at first, turn out to be closer than expected when you do see them?" In qualities of hearing section, scores for the mTBI group were the lowest for questions 14, 15, and 18 in comparison to all the other groups. These questions ask, "Do you have to concentrate very much when listening to someone or something?", "Do you have to put in a lot of effort to hear what is being said in conversation with others?", and "Can you easily ignore other sounds when trying to listen to something?"

Based on the data from the current study, there are some questions on the SSQ that may be of particular interest for evaluating auditory problems following mTBI. In the speech section, question 2 (related to understanding speech in quiet) had the smallest differences among groups and question 14 (relating to listening in the presence of two competing talkers) showed the highest differences among groups, with the mTBI group having the lowest scores, indicating greatest difficulty overall. In the spatial hearing section, there was a difference in mean scores of -2.5 between the HI and the mTBI groups for Question 1, regarding localizing a loud sound, suggesting that mTBI subjects do not have as much difficulty with this situation. Question15, pertaining to judging the distance of a sound, is the only question in this section where the mTBI group scores suggest more perceived difficulty than *any* of the other three groups. In the quality section, for questions 15 (needing extra effort to hear conversation) and 18 (easily being able to ignore background sounds), the mTBI subjects have the greatest relative difficulty compared to the YA, OA, and HI groups (differences of 6.4; 5.3; 3.4, respectively). In addition, mean differences for question 15 (perceived effort of conversation) indicate that the mTBI subjects reported, on average, more difficulty than HI group.

Discussion

Reported auditory processing problems post-concussion

This study addressed several research questions. The first evaluated whether self-reported symptoms of auditory processing problems were common in individuals who had experienced mTBI and continued to experience chronic, on-going effects in their daily lives. The type and frequency of symptoms experienced were compared to those reported by age- and gender-matched peers with no history of head injury.

Previous studies have suggested that a significant portion of individuals, (between 16-50%), have evidence of central auditory dysfunction following mild to severe TBI (Bergermalm & Lyxell, 2005; Cockrell & Gregory, 1992). Unlike these previous studies, the current study focused only on mild TBI and only on those who continued to be symptomatic within a defined time period (3-18 months) post-injury. Using a 50% criterion for the APS (i.e. scoring at least 12 out of 24), scores for two-thirds of the mTBI subjects had strong evidence difficulty processing auditory information. An even lower criterion may be warranted as almost all of the mTBI subjects scored 25% or higher on this questionnaire, in contrast to only four of the un-injured age- and gender-matched controls. The group difference in mean scores was highly significant for both the total score and for each individual question. Therefore, based on self-reported symptoms, the prevalence of central auditory dysfunction in this group could be 66% or greater.

The most prevalent problem for the mTBI subjects in this study was difficulty hearing in background noise, while few control subjects reported any problems in this situation. Difficulty hearing in background noise in the presence of normal peripheral hearing is one of the hallmark symptoms of central auditory processing disorder (Bamiou, Musiek, & Luxon, 2001; Jerger & Musiek, 2000; Vanniasegaram, Cohen, & Rosen, 2004). Another highly reported symptom in this group was difficulty understanding rapid or muffled speech. As understanding in a background of noise and understanding rapid speech are both examples of degraded listening conditions that are among the most frequent behavioral signs of CAPD, it is not surprising that these two items were the most highly correlated with each other on the APS. Speech tests that assess recognition of degraded speech stimuli are one of the main categories of central auditory tests that make up the ASHA guidelines for diagnosing CAPD (ASHA, 2005).

Sensitivity to loud noises was another major symptom reported by the mTBI subjects and was highly correlated with difficulty hearing in background noise. Actual rates of increased sensitivity to sound in central auditory processing disorders are not well documented, likely due to the subjective nature, but there are several central auditory mechanisms that may account for these loudness tolerance problems including an increase in sensitivity of neurons in the central auditory pathway or reduced central inhibition (Jastreboff & Jastreboff, 2004).

Sensitivity to noise is also a frequently reported symptom following head injury that has been widely reported in the general concussion literature (Landon, Shepherd, Stuart, Theadom, & Freundlich, 2012) and military populations with blast-related TBI (Fausti, Wilmington, Gallun, Myers, & Henry, 2009). A recent study found noise sensitivity to be of particular interest following concussion and as it was highly correlated with cognitive symptoms, such as memory problems and difficulty concentrating (Dischinger, Ryb, Kufera, & Auman, 2009). Reduced loudness tolerance is also strongly related to tinnitus. Two-thirds of the mTBI subjects in the current study reported experiencing tinnitus at least sometimes. Both loudness tolerance problems and tinnitus have complex causes that frequently cannot be determined, so it may not be possible to determine that these symptoms originate from the central auditory system. Regardless, the current results indicate that both are commonly reported by individuals who experience long term post-concussion problems.

Of the remaining symptoms, two of the most commonly reported by the mTBI subjects on the APS were difficulties paying attention when people talk and memorizing information obtained by listening. Paying attention to and remembering information obtained by listening require both intact central auditory function and higher order cognitive functions that have a top-down effect on auditory processing. Attention and memory impairments are the two most common forms of dysfunction following mTBI (Niogi et al., 2008). Just from this questionnaire, it is unknown whether the participants experienced attention and memory problems in just the auditory modality or in other modalities, as well. In the true definition of CAPD, attention and memory deficits must be limited in the auditory modality or less pronounced in other modalities (American Speech-Language-Hearing Association, 2005). It is possible that self-reported symptoms related to these two particular questions could be related to impaired general cognitive processing, central auditory dysfunction, or some combination of factors.

The relationship between auditory and other post-concussion symptoms

A second major question addressed the relationship between symptoms of possible central auditory dysfunction and other common post-concussion symptoms such as depression, fatigue, anxiety, and PTSD reported in the same subjects. Physical, psychological, and cognitive symptoms are all part of post-concussion syndrome, and many questionnaires are available to evaluate these symptoms. In general, these widely used post-concussion questionnaires do not address auditory symptoms, except for sensitivity to loud noises and physical symptoms of tinnitus and imbalance. In all, five other symptom questionnaires for different categories of common symptoms were given to subjects in this study and our results showed that scores for each of them were strongly correlated with scores for self-reported symptoms of auditory processing problems on the APS. The scores for the general post-concussion symptom questionnaire, the Rivermead, were the most highly correlated with the APS. This may be due to the overlap in some questions, such as sensitivity to noise and difficulty remembering, and the fact that the general purpose of the Rivermead was a measure of severity of symptoms after concussion. Higher rates of auditory problems in this study were also strongly related to higher self-reported rates of depression and fatigue, as measured by the BDI and the FSS. Symptoms of anxiety and PTSD were also significantly correlated with self-reported auditory processing problems, although not as strongly as the other symptoms. Fausti et al. (2009) reported that the underlying auditory symptoms can overlap with PTSD symptoms. In fact, central auditory deficits can often be mistaken for PTSD, causing increased emotional stress and frustration for patients.

Cause and effect relationships among these various symptoms are not easy to determine. To process speech, the listener needs to concentrate on the speaker without many distractions at the same time. Fatigue, headaches, or anxiety could affect an individual's ability to listen to and to process speech. The reverse may also be true: if it is difficult to understand auditory information, fatigue, frustration, and difficulty concentrating could occur. It is also true that self-reported symptoms do not always correlate with behavioral test performance. Spencer, Drag, Walker, and Bieliauskas (2010) completed a study in veterans of recent military operations and found that there is often not a significant correlation between self-reported cognitive symptoms and objective neuropsychological testing. The findings suggested that self-report symptoms may not be a valid indicator of actual clinical impairment. Subjective self-report measures can also be influenced by many factors, including the day the tests or questionnaires were completed, the current mood and physical symptoms of the participant, and wording of the questions, among other issues.

The results of this study show that self-reported symptoms of auditory processing problems are not only frequent, but they increase as the rate of other physical, psychological and cognitive symptoms increase in individuals with long-term effects due to mTBI. Because of this relationship and the potential lack of correlation between self-reported symptoms and actual test performance, caution is warranted in interpreting the overall study results as direct evidence of central auditory dysfunction. However, the results do suggest that difficulty with auditory information can be considered part of the post-concussion symptom profile in those with long-term problems following mTBI.

Change in symptoms over time

The third research question evaluated whether there were changes in self-reported symptoms of auditory processing problems over time, by readministering the same questionnaire at a later date. In general, the sub-set of mTBI subjects who completed the follow-up APS questionnaire was still experiencing a significant number of auditory symptoms 4-25 months after their initial participation. Differences in scores for half of the subjects showed little change in self-reported symptoms. Of those who had changes in their scores, three showed improvement, while three had worsening scores. It is interesting to note that the individuals who initially scored the lowest on the APS, that is, reported the fewest auditory problems, were the ones who tended to feel that they their symptoms had worsened. Individuals with few initial symptoms may have felt that their symptoms should have been resolved by the later date and therefore scored higher the second time they filled out the questionnaire due to the frustration with the on-going difficulties. The reverse was noted with those who initially reported a high number of symptoms. These subjects may have habituated to the problems over time or may have, in fact, experienced recovery.

As a group, there was not a significant change in reported auditory processing problems, and the scores from the two time points were not significantly correlated with each other. These results are likely due to the small number of subjects who completed and returned the second questionnaire. It is, also, not known whether these participants felt that their overall post-concussion symptoms (not just auditory) had changed. Further research is required to address whether symptoms consistent with auditory processing problems may change over time in the post-concussion period.

Use of a hearing disability questionnaire and comparison to groups with auditory problems

The final research question explored the application of a published hearing disabilities questionnaire that has previously been used primarily to evaluate hearing aid benefit in a population with mTBI. The self-reported auditory problems from this questionnaire were compared to published data from other groups who may experience difficulties hearing and understanding auditory information, including those with peripheral hearing loss and aging adults. Although the APS questionnaire was designed to address some of the most common auditory processing problems associated with central auditory processing dysfunction, it only addressed 12 broad questions, and the response scale did not allow for a very fine gradation of symptoms. It was interesting, therefore, to see how the mTBI subjects responded to the SSQ, a more detailed look at auditory symptoms in the categories of speech understanding, spatial listening, and quality of auditory information. It has been suggested that the SSQ may be sensitive to differences in auditory problems experienced among groups with normal or near-normal peripheral hearing who may have central auditory differences due to aging (Banh, Singh, & Pichora-Fuller, 2012). These researchers found significant differences between younger and older groups in self-reported difficulty on 42 out of 46 questions for the SSQ, indicating age-related differences in how these groups perceived and processed auditory information. As there was little peripheral hearing loss and aging is known to affect the central auditory system (e.g. Martin & Jerger, 2005), these group differences suggest that the SSQ may be sensitive to central auditory processing dysfunction.

The results of the current study showed that individuals with mTBI reported difficulty on many of the items on the SSQ. In general, average scores reported by the mTBI subjects were lower than the means for either the younger or older adult groups with normal or near-normal hearing in the study by Banh et al. (2012), suggesting that the mTBI subjects had comparatively more difficulty in every subsection. Some of the questions on the SSQ that showed the most difficulty for the older adults compared to the younger adults in the Banh et al. (2012) study were related to cognitive function and attention. The average scores for these same questions for the mTBI subjects in the current study were at least 2.1 points lower than the average scores for the older adults. These comparisons between the mTBI subjects and the younger vs. older adult groups with normal hearing may be consistent with the idea that there is a higher rate of auditory processing problems (whether due to central auditory dysfunction or top-down cognitive influences) due to mTBI than is seen as a result of the normal aging process.

In comparison to older adults with peripheral hearing loss (Gatehouse and Noble, 2004), the mTBI subjects in the current study reported less perceived difficulty across most items in the SSQ. For a few of the individual questions, however, the comparison of mean scores suggested that the mTBI subjects had more difficulty than those with a hearing loss. Two such questions addressed determining the spatial location of sound. Sound localization is a complex process that generally has to do with analyzing and comparing time and intensity differences of sound arriving at the two ears. This analysis takes place in the central auditory system at the level of the brainstem. Trauma-related acceleration, deceleration or rotational forces on axons could cause neural dysfunction at this level of central auditory processing, in turn affecting the transmission of information to higher levels of the pathway. This may explain why the mTBI subjects reported more difficulty with these items than did a group with peripheral hearing loss.

Another question that appeared to be more difficult for the mTBI subjects compared to hearing-impaired adults was in the qualities of speech section related to the ability to ignore competing sounds. As discussed above, difficulty listening in competing background noise was the most often reported symptom on the APS. Although this situation is also frequently rated as difficult for individuals with peripheral hearing loss, it may be at least perceived as more difficult for those who may have central auditory or cognitive dysfunction.

While there are limitations to comparing across studies (e.g. difference in age, number of subjects, test methods) these results suggest that using the SSQ may be informative for use in populations with possible central auditory dysfunction, including those with head injury. Although the APS was more general with fewer response choices (yes, sometimes, no) and the SSQ more detailed with a 10 point response scale, aspects of the two questionnaires were significantly related. The quality of hearing section on the SSQ was most strongly related to the overall scores on the APS. This is not surprising, as the quality hearing questions specifically target the difficulty listening in background noise/reverberation. The weaker correlation between the APS and spatial hearing items seems appropriate, as localizing was not reported as causing major difficulty on the APS. Although we may have expected a higher correlation between the APS and speech hearing questions, the number and types of situations represented on the SSQ may not have been well represented by the questions on the APS.

Questions such as those on the APS might be helpful in a case history or quick screening of auditory processing-related symptoms. The more detailed SSQ might be useful in helping determine individual targets for rehabilitation. This study along with the existing literature suggests that such questionnaires may be useful in adults who may have auditory problems not related to peripheral hearing loss, including individuals who may have acquired damage to the central auditory system as well those who have possible degenerative damage due to aging.

Conclusions

The present study focused on symptoms associated with central auditory processing difficulties in individuals who had suffered mTBI and chronic post-concussion symptoms. The main findings support the hypothesis that more symptoms of auditory processing difficulty would be reported in concussed subjects in comparison to control subjects. Among the most common problems were difficulty understanding speech in background noise and sensitivity to loud sounds.

Based on these results, there is evidence that symptoms, which are common in individuals diagnosed with CAPD, are also frequently reported in this specific population of individuals who have on-going problems following mTBI.

As hearing thresholds for all of the subjects were normal or near-normal, the possibility that these symptoms are caused by peripheral hearing loss has been ruled out. However, beyond the peripheral hearing system, this study has not concluded whether these symptoms are caused by central auditory or more global cognitive functioning, which could affect auditory processing in a top-down manner.

Not only were symptoms associated with auditory processing problems common in the mTBI group, they were highly correlated with many of the physical, cognitive, and psychological symptoms associated with post-concussion syndrome. This finding shows that these individuals can experience a broad range of problems in their daily lives for many months and years following mTBI, including auditory related problems. While cause and effect relationships among all these problems cannot be easily determined, it does point out the need for some caution in interpreting self-reported symptoms in the absence of clinical test results, as symptom reports may not predict actual functional deficits for either central auditory or cognitive-related tasks.

The findings of this study have some clinical implications for audiologists and other professionals. First, other professionals, including neuropsychologists and physicians, who see individuals with concussion may not be aware of the possible auditory effects. Communication with such professionals can help to inform them that referral to an audiologist who can assess peripheral and central auditory function may be in order for many post-concussion patients. Second, it is important for audiologists to know about relationships between head injury – even mild injuries – and possible central auditory dysfunction. Audiologists should be prepared to inquire about history of concussion and head injury, and if reported, obtain more detailed symptom history. Questionnaires like the APS and SSQ may be beneficial in targeting the specific auditory processing problems. Based on the patient's concerns and difficulties and the peripheral audiometric test results, a complete central auditory test battery may be warranted. Such testing is suggested not to apply a diagnosis of CAPD, but to better determine the levels of processing that may affected and provide a basis for individualized rehabilitation.

Auditory rehabilitation might be an appropriate treatment option in conjunction with other rehabilitation therapies for the concussion/mTBI patient. Auditory training skills take into consideration both neurocognitive mechanisms (bottom-up) and attentional processing (top-down). Components of an auditory rehabilitation program could include information counseling to provide communication strategies, direct listening training, auditory-based cognitive training, and possibly use of technology such as assistive listening systems to improve listening in noise. A recent study, showing improvement in both central auditory processing and cognitive abilities after eight weeks of auditory-based rehabilitation, provides some encouraging evidence that this type of approach may be beneficial (Murphy et al., 2011).

Further research is needed to more fully describe the relationship among concussion, long-term post-concussion symptoms, and central auditory processing problems. In general, it appears that difficulty listening in background noise, listening to rapid speech, and sensitivity to loud sound are frequent problems in the post-concussion period. Performance on behavioral auditory tests of central auditory function, electrophysiological testing of the central auditory system, and cognitive and psychological evaluations may provide evidence to indicate whether these common symptoms reflect central auditory dysfunction, top-down cognitive influences, or some combination of these factors.

Figures

Figure 1:

Anatomical diagram of the **peripheral** auditory system showing the outer, middle and inner ear (Porter & Tharpe, 2010).

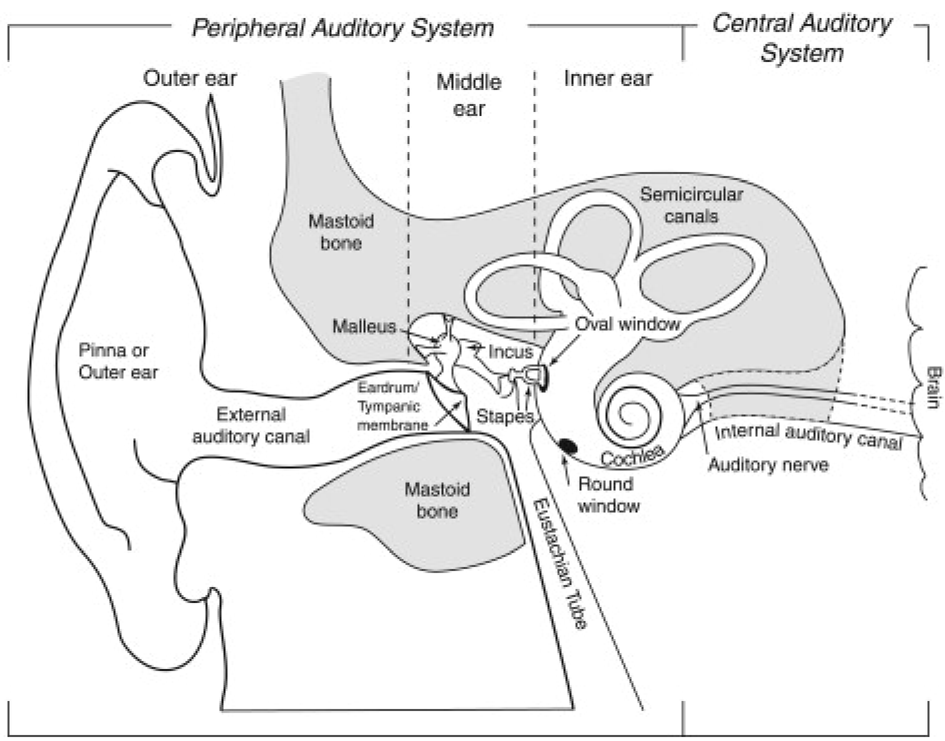


Figure 2:

Diagram of the **central** auditory system showing the main components of the pathway including the left and right auditory nerves, brainstem nuclei, and the auditory cortices (Heeger, 2006).

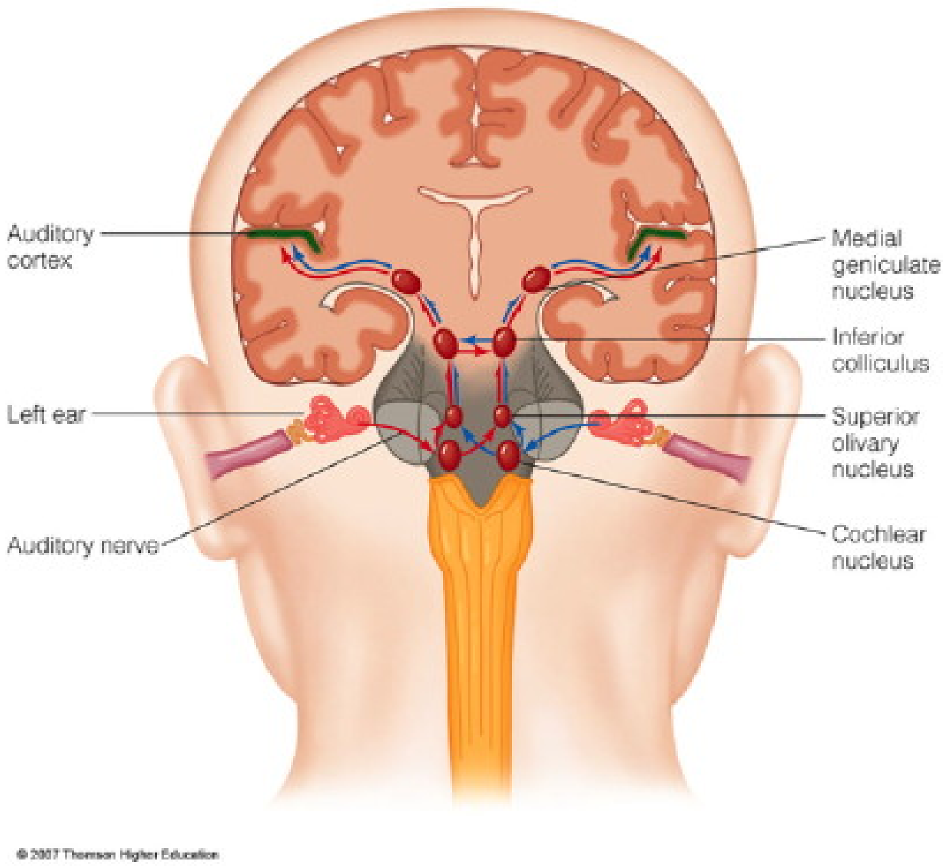


Figure 3:
Mean audiometric thresholds for the mTBI (black) and control (gray) groups. Error bars represent standard deviation.

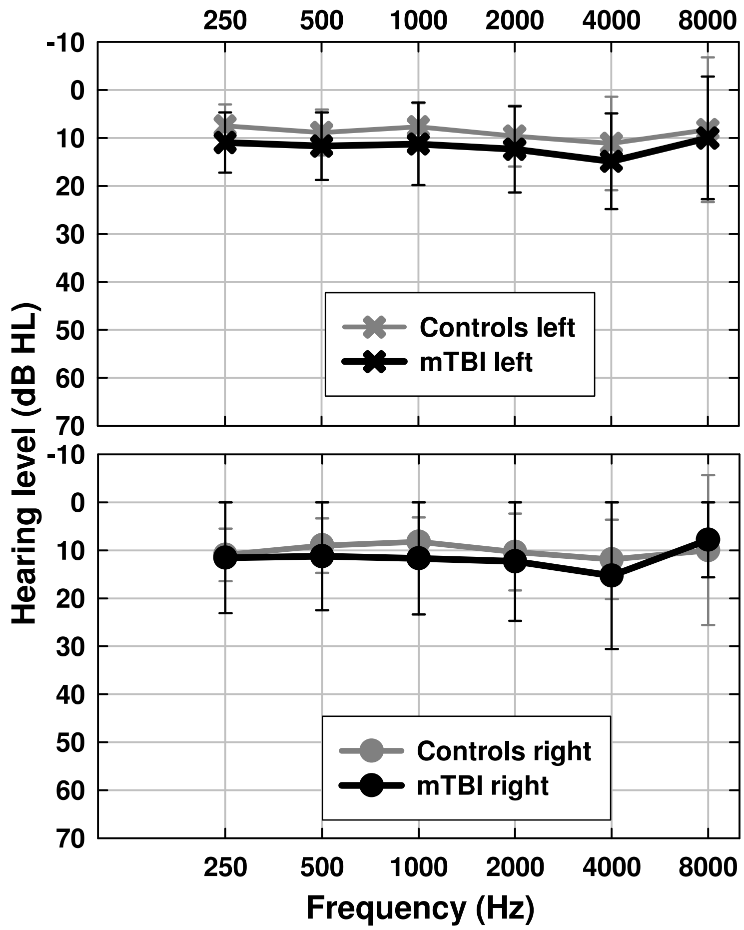


Figure 4:
Mean scores for the APS1 for the mTBI (black) and control (gray) groups out of a possible score between 0 and 24. Error bars represent standard deviation.

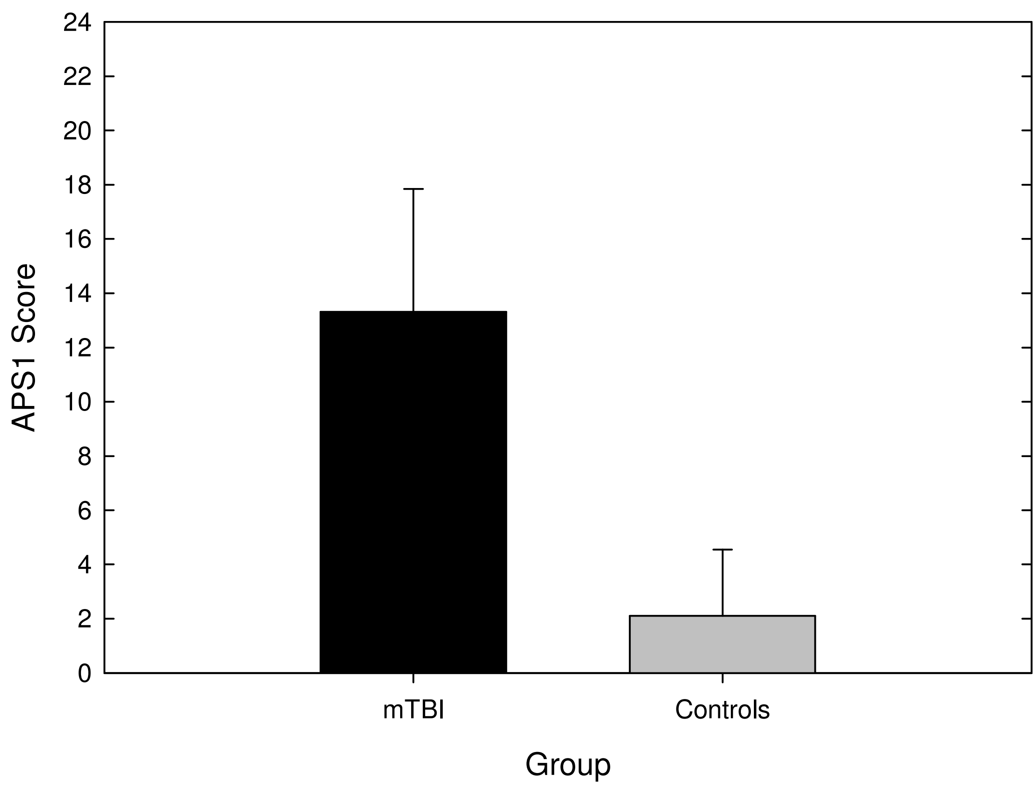


Figure 5:

Mean response per question on the APS1 for mTBI (black) and control (gray) subjects regarding whether each symptom is experienced, where 0 = no, 1 = sometimes, and 2= yes. Error bars represent standard deviation.

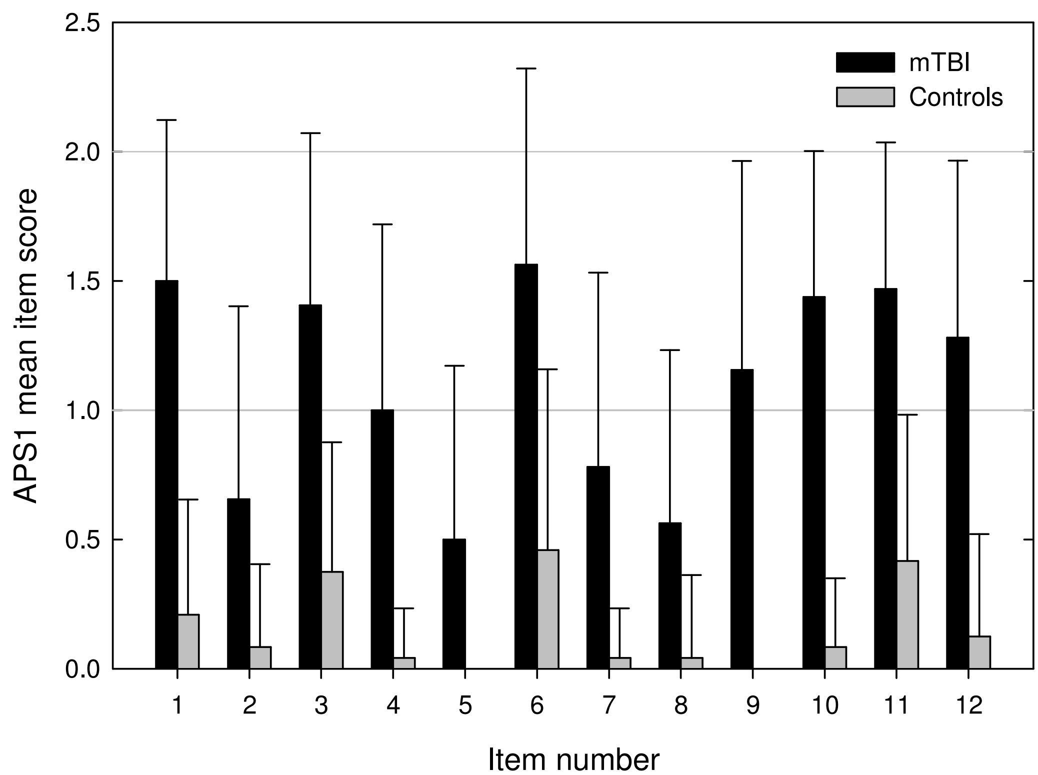


Figure 6:

APS1 item analysis of the percentage responses in each category for the top 5 scoring items for the mTBI group (left panel) compared to the control group (right panel): Yes (black), Sometimes (hashed), or No (gray).

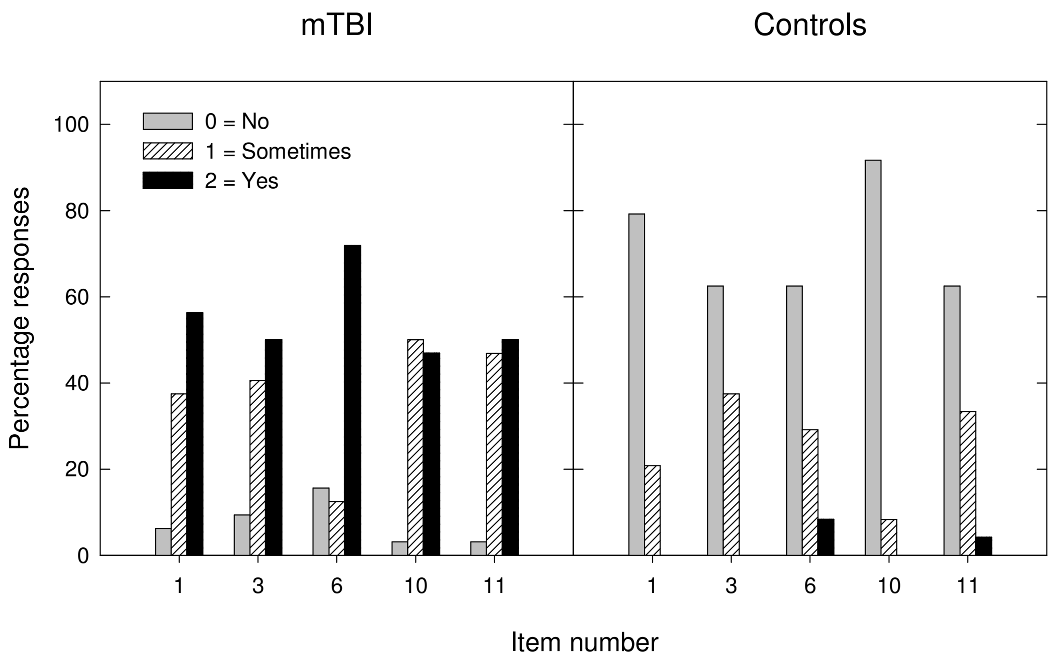


Figure 7:

Scatter plots of APS1 (x-axis) scores for mTBI and control subjects in relation to their individual scores on all other questionnaires (y-axis). RPQ3 and RPQ13 are sub-scores from the Rivermead Post-concussion Questionnaire. Pearson's correlation coefficients are indicated on each scatter plot.

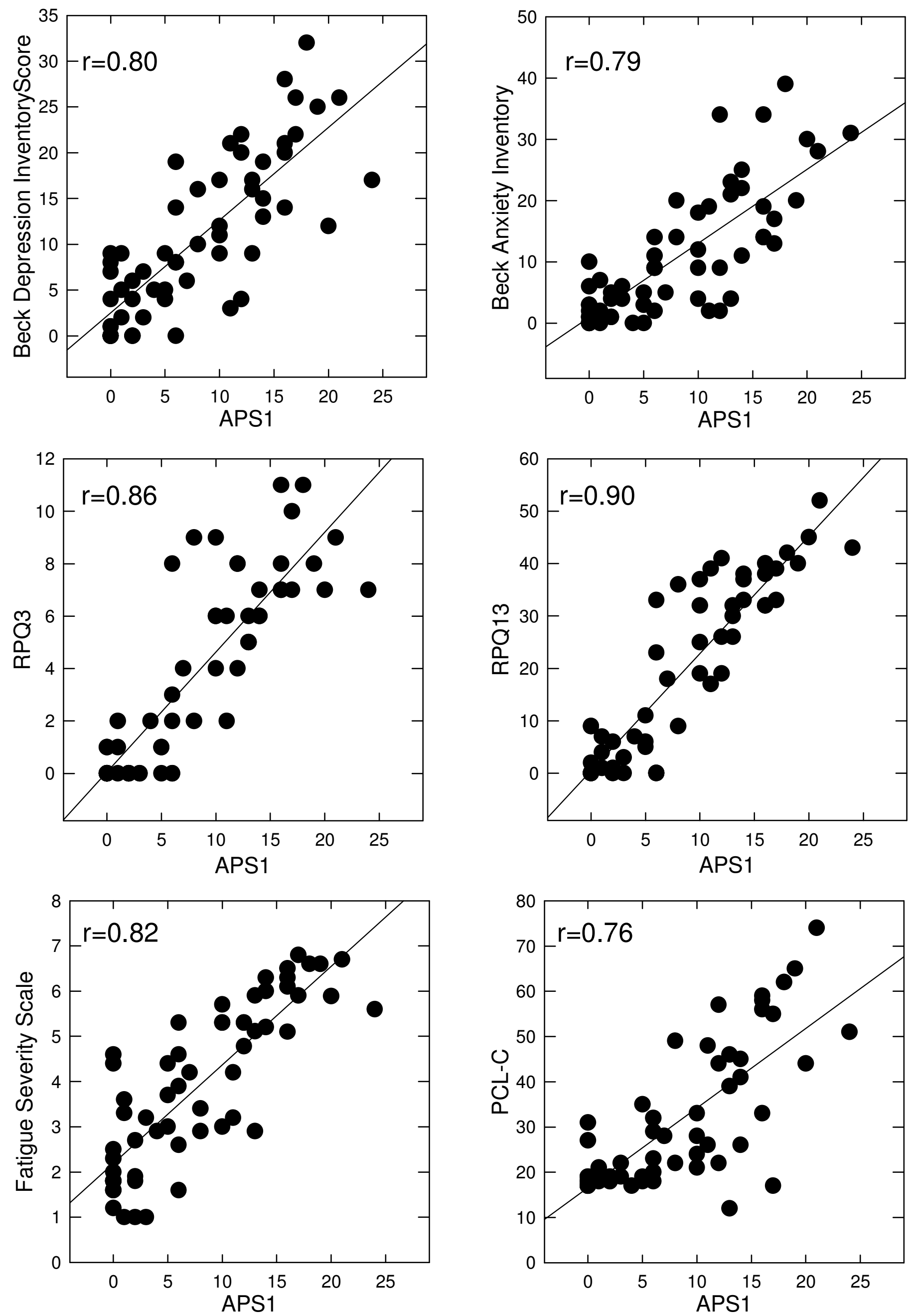


Figure 8:

Scores for mTBI subjects on the APS for the first and second administration. APS1 scores are indicated on x-axis and APS2 scores are shown on the y-axis. Reporting better scores the second time will show below the diagonal line while reporting worse scores will show above the diagonal line. For ease of visualization, identical scores were plotted with a small offset.

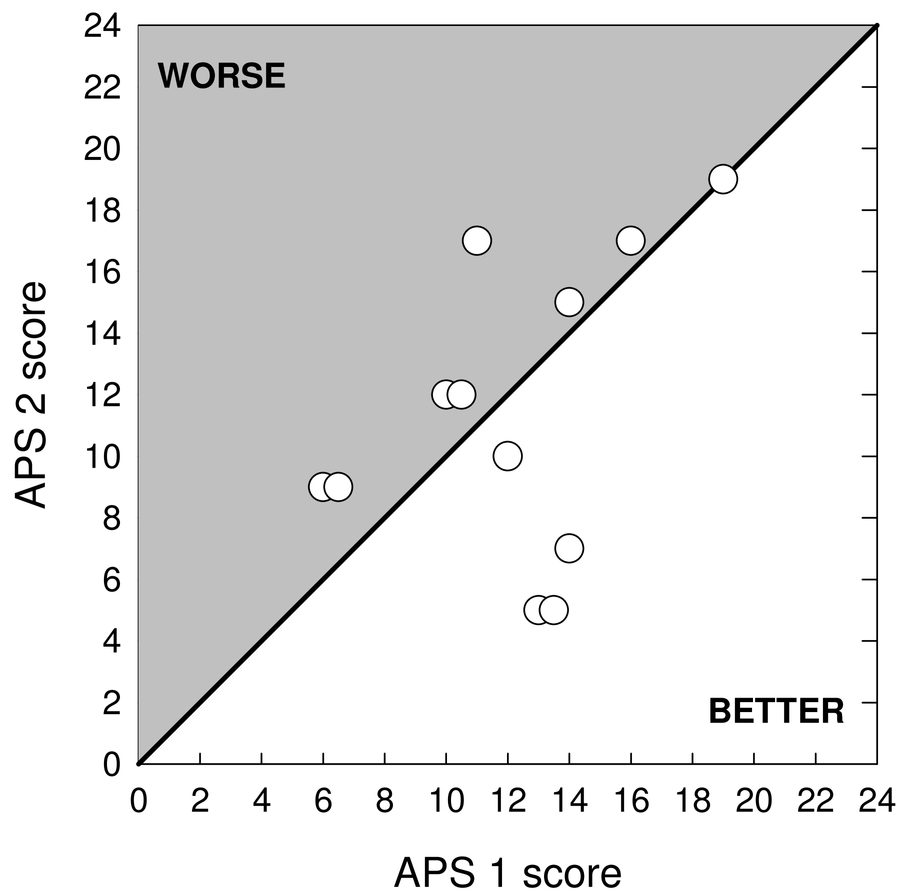


Figure 9:

Average scores on the SSQ from the current study in comparison to data from published data on the SSQ for younger adults (YA) and older adults (OA) with normal hearing or minimal hearing loss (Banh, Singh, & Pichora-Fuller, 2012) and in hearing-impaired adults (HI) (Gatehouse & Noble, 2004).

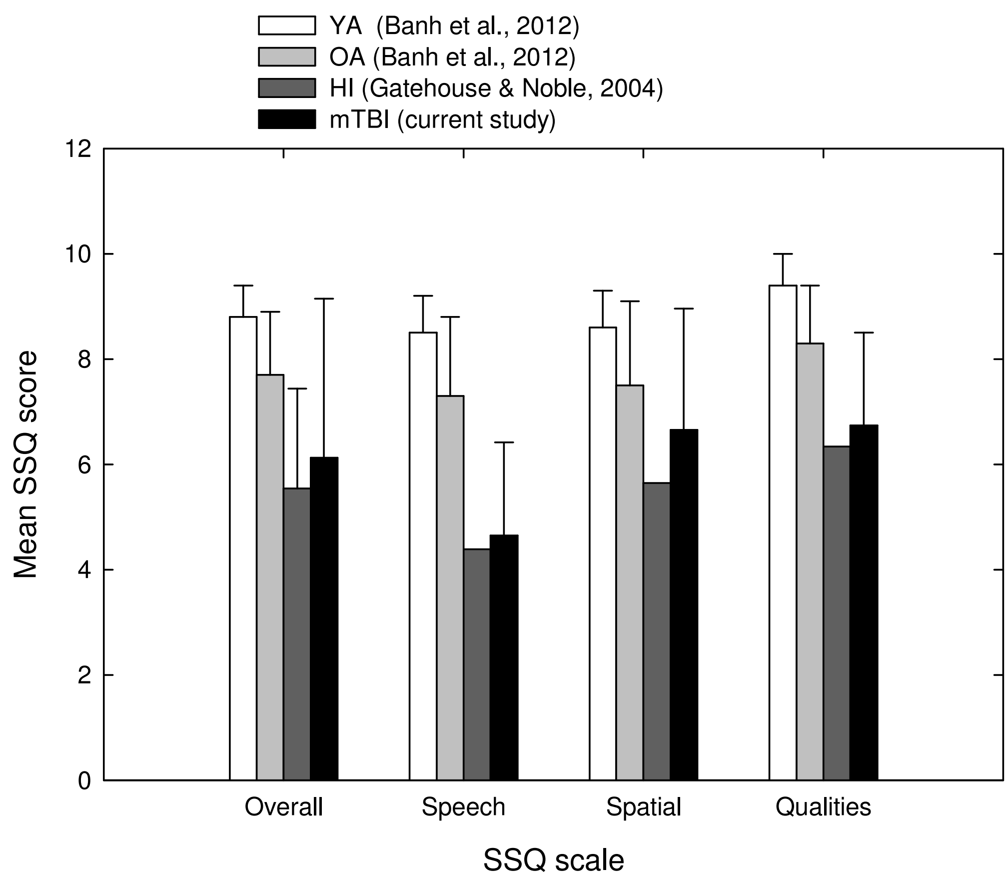
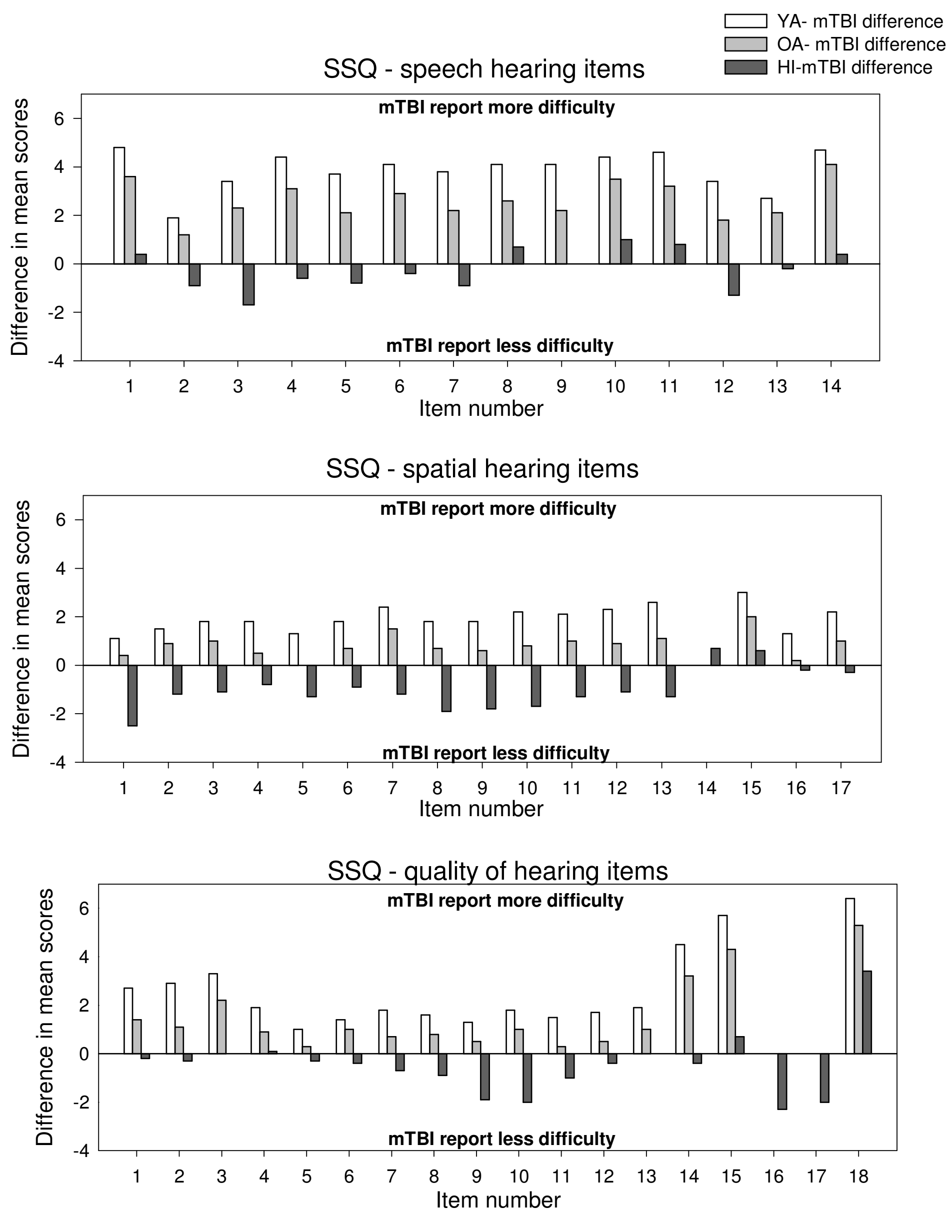


Figure 10:

Bars represent the difference in mean scores for each question on the SSQ between groups of subjects with mTBI in the current study and two previously published studies using the data shown for each question in Table 2. The mean for the mTBI subjects was subtracted from the mean for each of the other three groups (YA-mTBI, OA-mTBI, and HI-mTBI). Because lower mean scores indicate more difficulty in a certain situation, a positive difference therefore suggests that the mTBI group had more difficulty with a given situation than the comparison group, while negative differences suggest that the mTBI group had less difficulty than the comparison group for the given situation.



Tables

Table 1:

Demographic information and scores for 12 mTBI subjects who completed the APS2 and SSQ questionnaires.

Subject	Age	Gender	Time between injury and APS1 (months)	Time between APS1 and APS 2 (months)	APS1 score	APS2 scores	APS change	Self-report of overall change	SSQ average score
M23	41.2	M	6.3	6.3	6	9	3	no answer	6.1
M24	48.4	M	4.2	6.2	6	9	3	same	8.6
M07	40.5	F	4.5	19.2	10	12	2	worse	6.8
M21	52.7	F	16.5	8.5	10	12	2	improved	6
M28	51.1	F	5.1	6	11	17	6	no answer	6.3
M22	55.7	M	4.4	7	12	10	-2	improved	6.6
M09	49.2	M	5.6	18.9	13	5	-8	improved	7.6
M29	47.5	F	8.7	4.5	13	5	-8	improved	8.4
M31	52.5	F	4.5	4	14	7	-7	improved	6.8
M20	59.8	M	4.2	12.6	14	15	1	same	3.5
M02	23.9	M	4.1	25.7	16	17	1	same	4.6
M04	57.9	M	4	22.7	19	19	0	same/ improved	2.2

Table 2:

Mean and standard deviation of scores per question of the SSQ for the current study compared to previously published mean data from other studies. Data from Young Adults/Older Adults comes from Banh et al. (2012) and data from Hearing Impaired adults comes from Gatehouse & Noble (2004). The topic of the question is summarized in the first column. Note that question order differed slightly and scores for three questions (spatial #14 and quality #16-17) were not reported by Banh et al (2012). All scores shown were matched by the text of the question across studies.

	Current study		Younger Adults (Banh et al 2012)		Older Adults (Banh et al. 2012)		Hearing Impaired (Gatehouse & Noble 2004)	
Speech Hearing Items	Mean	S.D.	Mean	S.D	Mean	S.D	Mean	S.D
1. Talking with one person with TV on	4.2	1.6	9.0	1.1	7.8	1.9	4.6	2.7
2. Talking with one person in quiet carpeted room	8.0	2.0	9.9	0.2	9.2	1.2	7.1	2.4
3. Conversation 5 people quiet with vision	6.2	2.0	9.6	0.7	8.5	1.9	4.5	2.7
4. Conversation 5 people noise with vision	4.0	2.4	8.4	1.0	7.1	2.2	3.4	2.3
5. Talking with one person in continuous noise	5.4	3.0	9.1	1.1	7.5	2.1	4.6	2.4
6. Conversation 5 people noise without vision	3.1	2.4	7.2	1.4	6.0	2.1	2.7	2.2
7. Having conversation in echoic environment	4.9	2.4	8.7	1.3	7.1	2.0	4.0	2.4
8. Ignore interfering voice of same pitch	4.2	2.9	8.3	1.3	6.8	2.2	4.9	2.4
9. Ignore interfering voice of different pitch	5.0	2.7	9.1	0.9	7.2	2.1	5.0	2.6
10. Talk with one person and follow TV	2.0	2.2	6.4	1.7	5.5	2.4	3.0	2.6
11. Follow one conversation when many people talking	3.5	2.1	8.1	1.4	6.7	2.2	4.3	2.6
12. Follow conversation switching in a group	5.3	2.6	8.7	1.3	7.1	1.8	4.0	2.4
13. Have conversation on telephone	7.0	2.6	9.7	0.5	9.1	1.3	6.8	2.1
14. Follow one person speaking and telephone	2.1	2.4	6.8	1.9	6.2	2.6	2.5	1.8

Spatial Hearing Items	Current study Mean	Current study S.D.	Younger Adults Mean	Younger Adults S.D	Older Adults Mean	Older Adults S.D	Hearing Impaired Mean	Hearing Impaired S.D
1. Locate lawn mower	7.1	2.2	8.2	1.1	7.5	2.2	4.6	2.7
2. Locate speaker around a table	6.8	2.2	8.3	1.1	7.7	2.1	5.6	2.8
3. Lateralize a talking to left or right	8.1	2.3	9.9	0.3	9.1	1.1	7.0	2.6
4. Locate a door slam in unfamiliar house	6.9	2.8	8.7	1.3	7.4	2.4	6.1	2.8
5. Locate above or below on stairwell	6.8	2.5	8.1	1.4	6.8	2.6	5.5	2.8
6. Locate dog barking	6.9	2.9	8.7	1.0	7.6	2.3	6.0	2.6
7. Locate vehicle from footpath	6.1	2.9	8.5	1.1	7.6	1.8	4.9	2.8
8. Judge distance from footsteps or voice	6.1	3.0	7.9	1.3	6.8	2.2	4.2	2.6
9. Judge distance of vehicle	6.3	2.8	8.1	1.3	6.9	1.8	4.5	2.7
10. Identify lateral movement of vehicle	6.5	3.1	8.7	1.0	7.3	2.3	4.8	2.7
11. Identify lateral movement from voice or footsteps	6.3	3.0	8.4	1.2	7.3	2.1	5.0	2.7
12. Identify approach or recede (voice or footsteps)	6.7	2.8	9.0	1.0	7.6	1.9	5.6	2.7
13. Identify if vehicle is approaching or receding	6.6	2.7	9.2	0.9	7.7	1.6	5.3	2.8
14. Sounds appear to be inside head rather than outside	6.8	3.6					7.5	2.3
15. Sounds closer than expected	5.5	2.6	8.5	1.7	7.5	2.0	6.1	2.2
16. Sounds further away than expected	7.5	2.2	8.8	1.3	7.7	1.9	7.3	2.2
17. Sounds in expected location	6.3	2.8	8.5	1.3	7.3	2.2	6.0	2.8

Qualities of Hearing Items	Current study		Younger Adults		Older Adults		Hearing Impaired	
	Mean	S.D.	Mean	S.D	Mean	S.D	Mean	S.D
1. Separation of two sounds	6.8	2.5	9.5	0.7	8.2	1.8	6.6	3.0
2. Sounds appearing jumbled	6.2	2.7	9.1	1.3	7.3	3.0	5.9	3.1
3. Music and voice as separate objects	6.3	2.8	9.6	0.8	8.5	1.8	6.3	2.7
4. Identify different people by voice	7.7	2.7	9.6	0.7	8.6	1.6	7.8	2.0
5. Distinguish familiar music	8.6	2.1	9.6	0.6	8.9	1.1	8.3	1.9
6. Distinguish different sounds	7.9	2.8	9.3	1.4	8.9	1.7	7.5	2.7
7. Identify different people by voice	7.3	2.6	9.1	1.3	8.0	1.6	6.6	3.0
8. Naturalness of music	8.1	2.0	9.7	0.7	8.9	1.0	7.2	2.6
9. Clarify of everyday sounds	8.5	1.8	9.8	0.5	9.0	1.1	6.6	2.7
10. Naturalness of other voices	8.0	2.0	9.8	0.6	9.0	1.1	6.0	2.5
11. Naturalness of everyday sounds	8.1	2.8	9.6	1.0	8.4	2.2	7.1	2.8
12. Naturalness of own voice	8.1	2.5	9.8	0.4	8.6	1.9	7.7	2.8
13. Judging mood from voice	7.5	2.3	9.4	0.8	8.5	1.1	7.5	2.5
14. Need to concentrate when listening	4.1	3.3	8.6	1.9	7.3	2.5	3.7	2.8
15. Effort of conversation	3.3	2.9	9.0	1.3	7.6	2.7	4.0	3.1
16. As driver, can you hear the passenger	6.9	2.8					4.6	2.8
17. As passenger, can you hear the driver	7.4	2.4					5.4	2.7
18. Ability to ignore competing sounds	1.9	2.3	8.3	1.7	7.2	2.6	5.3	3.1

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Appendix I: Auditory Processing Symptoms (APS) Questionnaire

Please check the most appropriate response to each of the following statements regarding your current situation (last 2 weeks). Choose yes if the problem occurs frequently and sometimes if it occurs only occasionally.

1. I have problems hearing and/or understanding in background noise or reverberation (echo/poor acoustics).	☐ Yes ☐Sometimes ☐ No
2. I have problems telling where sounds are coming from (localizing).	☐ Yes ☐Sometimes ☐ No
3. I have problems understanding rapid speech or muffled speech.	☐ Yes ☐Sometimes ☐ No
4. I have problems following spoken instructions.	☐ Yes ☐Sometimes ☐ No
5. I have problems discriminating (telling the difference between) one speech sound or word from another.	☐ Yes ☐Sometimes ☐ No
6. I am sensitive to loud sounds (bothersome or painful).	☐ Yes ☐Sometimes ☐ No
7. I respond inconsistently to sounds or when someone speaks to me (sometimes hear it and other times do not)	☐ Yes ☐Sometimes ☐ No
8. I have problems understanding on the phone.	☐ Yes ☐Sometimes ☐ No
9. I have problems reading and writing.	☐ Yes ☐Sometimes ☐ No
10. I have problems paying attention when people talk to me.	☐ Yes ☐Sometimes ☐ No
11. I have difficulty memorizing information learned by listening.	☐ Yes ☐Sometimes ☐ No
12. I have problems finding words and expressing myself.	☐ Yes ☐Sometimes ☐ No

Summary of Capstone Project

Mild traumatic brain injury (mTBI), also known as concussion, has emerged as a major public health concern in the United States and worldwide. Of the estimated 1.7 million head injuries that occur nationally each year, about 75% are mTBI. Although the majority of individuals recover quickly from this "mild" injury, a significant number of individuals suffer long-term symptoms and disabling problems across a broad array of physical, cognitive, and emotional domains that can cause them difficulty returning to work or a daily routine. With nearly $17 billion each year spent on treatment and rehabilitation of mTBI in the U.S.A., the impact is significant both at individual and global levels.

Any part of the brain can be affected by head injury, and the auditory system is vulnerable at all levels. Although peripheral hearing loss due to mTBI is not common, there is increasing evidence that central auditory processing deficits can occur post-mTBI. Depending on where damage occurs within the pathway, individuals could experience a variety of auditory processing problems, affecting the way they are able to recognize, interpret, and use information they hear. The goals of this study were to better understand the incidence and types of auditory processing problems reported by people who have any (physical, emotional, and/or cognitive) long-term problems following mTBI, and how central auditory-related symptoms may fit within the overall post-concussion symptom profile of these individuals. Our working hypotheses were that 1) auditory processing problems would be more prevalent in mTBI subjects than in age- and gender-matched control subjects; 2) auditory processing problems would correlate with

other cognitive, physical, and emotional post-concussion symptoms; 3) self-reported auditory processing problems would change over time as an individual recovers in the long-term; and 4) that use of a published auditory disabilities questionnaire in individuals with mTBI would reveal that the group experienced a pattern of auditory-related difficulties that may reflect central auditory processing problems.

To test these hypotheses, 32 adults with mTBI and 27 age- and gender-matched control subjects were enrolled. The mTBI subjects were recruited from a concussion management and rehabilitation program and tested between 3 and 18 months post-injury. Therefore, this group represented the proportion of individuals who have long-term post-concussion problems. All participants were verified to have normal or near-normal hearing, so that peripheral hearing loss could be ruled out as a cause of auditory problems.

Outcome measures were self-reported symptoms obtained using a series of questionnaires across several domains. Auditory processing-related symptoms (APS) were assessed using a set of 12 questions based on the most common symptoms of central auditory processing disorders. This questionnaire was completed at two time points in a subset of 12 mTBI subjects who returned questionnaires by mail. A second auditory-related questionnaire called the Speech, Spatial, and Qualities of Hearing Scale (SSQ), which was previously designed for evaluating hearing aid benefit, was also completed by the subset of 12 mTBI subjects. The remaining five questionnaires evaluated self-reported symptoms of depression, anxiety, fatigue, post-traumatic stress, and overall physical, cognitive, and emotional symptoms commonly associated with post-concussion syndrome. Between-group differences in scores on each questionnaire, as well as correlations among individual questions and across questionnaires, were evaluated.

The main finding of the study was that symptoms associated with central auditory processing problems were reported at high rates among individuals with long-term problems following mTBI. The most commonly reported symptoms in this group were difficulty understanding speech in background noise, sensitivity to loud sounds, difficulty understanding muffled or rapid speech, and difficulty with attention-dividing tasks. In contrast, very few of the age- and gender-matched controls reported any of these symptoms. Differences in scores between mTBI and control groups were highly significant for each individual APS question, as well as the overall score.

A second finding was that self-reported auditory processing problems were highly correlated with symptoms in all the other domains. The relationship was strongest for scores on the general concussion symptoms, depression, and fatigue questionnaires, but anxiety and post-traumatic stress scores were also strongly correlated with scores on the APS questionnaire. These results indicate that high rates of self-reported auditory processing problems co-occurred with high rates of many physical, cognitive and psychological post-concussion symptoms.

Of the mTBI subjects who completed the second APS questionnaire at a later time point, some reported improvement in auditory-related symptoms several months later while others reported that these symptoms worsened over time. Individuals who felt their symptoms had worsened were generally the subjects who initially reported few symptoms, while subjects who reported improvement were generally those who reported the most problems at the time of the initial testing. For the group as a whole, there was not a significant difference in scores from first questionnaire to the second, indicating that auditory processing problems continued to affect the subjects' daily lives over a long period post-concussion. More information about the overall symptoms at the second time point, better control of the time periods assessed, and a larger number of participants would be necessary to provide more evidence regarding changes in auditory related symptoms over time.

The subset of mTBI subjects also completed the SSQ, a questionnaire assessing hearing and listening problems in speech understanding, spatial listening, and quality of speech domains. SSQ scores in this mTBI group were compared to published normative data from 1) normally hearing younger adults; 2) older adults with normal/near-normal hearing and possible age-related auditory processing problems; and 3) adults with peripheral hearing impairment. Overall, the mean scores from the mTBI subjects in this study were consistent with more auditory related difficulty than groups of normal hearing (un-injured) adults, either younger or older, but slightly less difficulty than the hearing-impaired older adults across the three domains. These results suggest that such a questionnaire may be sensitive to problems listening and processing information in the auditory domain experienced in the long-term following mTBI.

This study contributes to the current literature on auditory processing problems post-concussion. It is among the first to consider only individuals with mild TBI, rather than mixed groups or more severe TBI, and to focus on individuals known to have on-going post-concussion problems within a defined time period. The high rates of symptoms that may be associated with central auditory processing problems in this group suggest a need for greater awareness among professionals who work with the post-concussion population of the possible need for referral to an audiologist for evaluation. If standard audiometric testing shows normal hearing thresholds, but reports disproportionate problems listening to, remembering, and understanding auditory information, a battery of central auditory tests including behavioral and electrophysiological tests could help identify whether the problems are due to damage within the central auditory system. A multi-disciplinary team approach may be necessary to best determine the influence on of top-down cognitive processing factors, such as auditory attention and memory on an individual’s symptoms. It is also important for audiologists to consider a history of previous head injury for any individual who may have more difficulty hearing and listening than his/her audiogram might predict. In terms of intervention, auditory-based rehabilitation may be appropriate for some individuals with mTBI. Such rehabilitation could include information counseling, direct listening training, auditory-based cognitive training or possibly use of devices such as personal FM systems to improve listening in noise.

Overall, it is important to take away from this study that “mild” head injuries are not necessarily minor and can cause persistent symptoms of auditory processing dysfunction. Further research is needed to better understand the relationship between self-reported symptoms that might be linked to central auditory processing dysfunction and behavioral and electrophysiological test findings. A better understanding of such relationships could allow for earlier diagnoses and development of individualized intervention for this subset of mTBI victims who continue to experience long-term complications.