Research Article

Auditory and Cognitive Behavioral Performance Deficits and Symptom Reporting in Postconcussion Syndrome Following Mild Traumatic Brain Injury

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Purpose: This study examined auditory deficits and symptom reporting in individuals with long-term postconcussion symptoms following a single mild traumatic brain injury (mTBI) compared to age- and gender-matched controls without a history of mTBI.

Method: Case history interviews, symptom questionnaires, and a battery of central auditory and neuropsychological tests were administered to 2 groups. The mTBI group was a civilian population recruited from a local concussion management program who were seeking rehabilitation for postconcussion-related problems in a postacute period between 3 and 18 months following injury. Symptom validity testing was included to assess the rate of possible insufficient test effort and its influence on scores for all outcome measures. Analyses of group differences in test scores were performed both with and without the participants who showed insufficient test effort. Rates of symptom reporting, correlations among symptoms and behavioral test outcomes, and the relationships between auditory and cognitive test performance were analyzed.

Results: The mTBI group reported a high rate of auditory symptoms and general postconcussion symptoms. Performance on neuropsychological tests of cognitive function showed some differences in raw scores between groups, but when effort was considered, there were no significant differences in the rate of abnormal performance between groups. In contrast, there were significant differences in both raw scores and the rate of abnormal performance between groups for some auditory tests when only considering participants with sufficient effort. Auditory symptoms were strongly correlated with other general postconcussion symptoms.

Conclusions: Significant auditory symptoms and evidence of long-term central auditory dysfunction were found in a subset of individuals who had chronic postconcussion symptoms after a single mTBI unrelated to blast trauma. The rate of abnormal performance on auditory behavioral tests exceeded the rate of abnormal performance on tests of cognitive function. **Supplemental Material:** <https://doi.org/10.23641/asha.8329955>

Mild traumatic brain injury (mTBI), also known as *concussion*, is recognized as a serious health issue worldwide. The Centers for Disease Control and Prevention has referred to mTBI as a silent epidemic, because many of the problems are not visible and they make up at least 75% of the over 1.7 million traumatic brain injuries (TBIs) sustained in the United States each year

(Centers for Disease Control and Prevention, 2014). Although labeled *mild*, for many, the effects of concussion are long-lasting and not at all minor. Whereas the majority recover fully without intervention in the first few weeks following mTBI, a significant minority experience long-term problems, which may be due to focal and diffuse metabolic and neurological changes throughout the brain that persist from weeks to years after injury (De Beaumont, Brisson, Lassonde, & Jolicoeur, 2007; De Beaumont et al., 2009; Henry, Tremblay, Leclerc, et al., 2011; Henry, Tremblay, Tremblay, et al., 2011). Those who continue to have symptoms (typically including headache, dizziness, fatigue, irritability, impaired memory and concentration, insomnia, and lowered tolerance for noise and light) beyond the first 3–6 months after injury are often referred by some as having *postconcussion syndrome* (e.g., Mittenberg & Strauman, 2000) or *co-occurring*

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Editor-in-Chief: Frederick (Erick) Gallun

Editor: Steve Aiken

Received July 13, 2018

Revision received December 13, 2018

Accepted February 15, 2019

https://doi.org/10.1044/2019_JSLHR-H-18-0281

Disclosure: The authors have declared that no competing interests existed at the time of publication.

postconcussion symptoms (Arciniegas, Anderson, Topkoff, & McAllister, 2005).

Physical, behavioral, emotional, sensory, cognitive, and communication deficits are all among the co-occurring sequelae that may persist for months and years beyond injury. While the mechanism, location, and force of specific injuries are highly heterogeneous, the brainstem, frontal lobe, and temporal lobes can be particularly vulnerable to injury against the bony ridges of the skull. Auditory processing dysfunction is an impairment that may not be apparent in standard audiometric testing, because hearing thresholds and speech recognition in quiet may be clinically normal. Rather, damage to structures along the pathway from the inner ear to the cortex may disrupt encoding and perceptual processing of auditory information in the central auditory nervous system, disrupting speech understanding and other auditory perceptual skills, such as sound localization, auditory discrimination, temporal aspects of audition, and hearing in degraded or noisy conditions. The auditory centers in the brain responsible for these skills are highly vulnerable to mTBI, including structures in the left temporal lobe and pathways between the thalamus and primary auditory cortex, the planum temporale, and the corpus callosum (Broglio, Pontifex, O'Connor, & Hillman, 2009; Cubon, Putukian, Boyer, & Dettwiler, 2011). Existing literature suggests that, across a range of severities, up to 50% of individuals with TBI-related injuries may have central auditory processing problems (Bergemalm & Borg, 2001; Bergemalm & Lyxell, 2005; Flood, Dumas, & Haley, 2005). Even in mTBI, evidence that a significant number of individuals have functional auditory processing problems in the long-term postconcussion is emerging, including those in military groups with blast and non-blast-related mTBI (Gallun, Diedesch, et al., 2012; Gallun, Lewis, et al., 2012; Oleksiak, Smith, St. Andre, Caughlan, & Steiner, 2015; Saunders et al., 2015) and in sports concussion (Turgeon, Champoux, Lepore, Leclerc, & Ellemberg, 2011).

The relationship among postconcussion symptoms of auditory dysfunction, more global cognitive factors, and behavioral and emotional problems is complex. One aspect that has received little attention in the auditory behavioral literature is the validity of test findings based on whether participants are putting forth good effort to perform to the best of their ability on each test. If individuals perform poorly across tests, it may be difficult to assess whether there are auditory deficits or global cognitive deficits, or if performance is influenced by psychological or emotional factors (Bigler, 2014). Symptom validity tests are frequently used by psychologists to distinguish cognitive impairment from poor effort, underperformance, and exaggeration. These tests are often forced-choice measures of memory recognition designed to be easy for those with cognitive impairment to perform well, and cutoff scores are validated to discriminate individuals demonstrating good versus suboptimal effort. It is possible that some individuals may exaggerate or deliberately perform more poorly in the face of possible financial compensation or obligations, such as returning to work. Even if an individual is not deliberately exaggerating, it is

well known that depression, anxiety disorders, posttraumatic stress disorder (PTSD), and sleep disturbances are common comorbidities following mTBI (Arciniegas et al., 2005). These symptoms and their impact on behavioral test performance may also be relevant to consider for the population who may be evaluated in an audiology clinic.

In the concussion literature as a whole, long-term effects of concussion that may persist for months and years have until recently received less attention than the acute stage after injury (McInnes, Friesen, MacKenzie, Westwood, & Boe, 2017), and there remains some controversy about the existence of a chronically, cognitively impaired subgroup of mTBI (Rohling, Larrabee, & Millis, 2012). Studies focusing on auditory effects have generally been longer term but have often included a very heterogeneous cohort, including individuals many years out, and combining various levels of TBI severity. Recent studies including military/veteran TBI populations provide much-needed additional information but may not generalize to civilian populations due to differences in mechanism of injury and presence of confounding variables, such as noise exposure and the prominence of psychological trauma (Davenport, 2016).

This study and other recent investigations (e.g., Hoover, Souza, & Gallun, 2017) address the questions of whether auditory performance deficits are prevalent/part of postconcussion problems and whether such deficits are specific to neurobiological damage within the central auditory system or more global cognitive and neuropsychological dysfunction. Here, we report on symptom reporting, functional auditory performance, and cognitive performance in a civilian population of individuals with long-term postconcussion symptoms 3–18 months following a single mTBI compared to age- and gender-matched controls without a history of concussion. Using a battery of tests, the goal was to identify the relative prevalence and relationship among auditory and cognitive test performance and symptomology. Importantly, in this investigation, we controlled for the effects of effort by including tests sensitive to symptom exaggeration that could compromise the validity of these behavioral outcomes.

Method

Participants

Thirty-two individuals diagnosed with mTBI and 32 healthy individuals without any history of concussion requiring medical intervention participated in the study. Individuals in the mTBI group were recruited from the patient population of a local outpatient brain injury rehabilitation and concussion management program. Potential participants referred for study inclusion were between 3 and 18 months postinjury and continued to report ongoing postconcussion symptoms. All had been diagnosed with mTBI using criteria drawn from the American Congress of Rehabilitation Medicine (1993). As the diagnosis was made by the referring neuropsychologist/clinic, results of imaging (computed tomography and/or magnetic resonance imaging) and reported signs and symptoms (e.g., confusion/disorientation,

slurred speech) were also used when possible but were not available in many cases. No subjects with a diagnosis of moderate or severe TBI were included, nor were individuals with penetrating trauma, blast, crush injury, or temporal bone fracture.

In order to minimize the influence of peripheral hearing loss, no participants with average hearing of greater than 40 dB HL (American National Standards Institute, 2010), as defined by the pure-tone average (PTA) of 1.0, 2.0, and 4.0 kHz or evidence of middle ear pathology by tympanometry or air–bone differences, were included. Additional exclusion criteria included preinjury history of neurological disorder, previous head injury requiring medical care, diagnosed learning disability or attention disorder, or history of severe psychiatric disorder.

An equal number of individuals in the healthy control group were recruited from among the population of Syracuse University and the surrounding community. The control group had no history of head injury but met the same additional inclusion/exclusion criteria and was recruited to achieve age- and gender-matching across groups. Group demographics are described in Table 1. All procedures for this study were approved, and participants provided written consent in compliance with institutional review boards of Syracuse University and SUNY Upstate Medical University.

Procedure

A subject interview including demographic information, audiological case history, and injury information (for the mTBI group) was completed. Each participant underwent a comprehensive audiometric evaluation, including air- and

bone-conduction audiometry using a Grason-Stadler GSI-61 audiometer and Etymotic ER-3A insert earphones. Tympanograms (226 Hz), acoustic reflexes, and reflex decay measures were collected using a Grason-Stadler Tymstar middle ear analyzer. Distortion product otoacoustic emissions (DPOAEs) were collected for f2 frequencies between 1.0 and 8.0 kHz using the Mimosa Acoustics HearID system using an f2/f1 ratio of 1.2. Audiometric evaluation was carried out with the subject seated on a comfortable chair in a sound-treated audiometric booth (ambient noise levels < 15 dB SPL at octave frequencies from 0.125 to 8.0 kHz).

All subjects who met inclusion criteria then completed a behavioral auditory test battery and a neuropsychological (cognitive) test battery (see Table 2). Participants also completed questionnaires to obtain self-reported symptoms related to central auditory processes and behavioral, emotional, and physical symptoms related to postconcussion syndrome. The auditory and neuropsychological test batteries were completed in two separate test sessions of approximately 2 hr each on separate days. A third test session was also completed for all subjects, which included electrophysiological testing. The results of the electrophysiological tests (auditory brainstem responses, cortical auditory evoked potentials, and auditory P3) are considered separately elsewhere and are not analyzed in this article. The order of the three test sessions were randomized across participants. Breaks were provided in each session to minimize fatigue.

Neuropsychological Test Battery

Cognitive impairments in the domains of executive function, learning and memory, attention, and processing

Table 1. Demographic data for participant groups.

Variable		Control (n = 32)			mTBI (n = 32)		
		M	SD	Range	M	SD	Range
Age (years)		41.7	13.4	19.1–60.7	42.3	13.1	18.1–60.0
Education (years)		16.3	2.6	12–21	15.3	2.9	12–22
Time postinjury (months)		—	—	—	6.6	3.8	2.9–18.4
		n	% of group		n	% of group	
Gender	Female	22	69		22	69	
	Male	10	31		10	31	
Employment status (preinjury)	Full time	18	56		23	72	
	Part time	8	25		2	6	
	Unemployed	3	9		1	3	
	No paid employment	3	9		5	16	
Marital status	Student	5	16		2	6	
	Never married	11	34		7	22	
	Married	19	59		21	66	
	Separated/divorced	2	6		3	9	
Members of household	Widowed	0	0		1	3	
	Living alone	6	19		1	3	
	Spouse/partner	18	56		22	69	
	Parents	2	6		5	16	
	Siblings	1	3		4	13	
	Child/children	11	34		20	63	
	Roommates	6	19		1	3	

Note. Em dashes mean “not applicable,” to indicate the control group does not have time postinjury.

Table 2. Mean and standard deviation of raw scores for neuropsychological and auditory behavioral tests by group.

Test	Subtest	Control		mTBI ALL			mTBI IE excluded		
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	Sig. ^a	<i>M</i>	<i>SD</i>	Sig. ^a
Neuropsychological tests									
CVLT	Trials 1–5 (<i>T</i> score)	56.2	8.5	51.2	14.2	.131	53.7	11.3	.362
	Short Free Recall	11.7	2.9	10.6	4.0		11.4	3.2	
	Long Free Recall	12.8	3.1	10.8	4.3		11.8	3.5	
DS	Forward	11.4	1.9	9.4	2.6	.004**	9.9	2.1	.017*
	Backward	8.4	2.3	6.9	2.4		7.3	2.2	
TMT	Trail A (s)	17.7	5.2	29.2	30.0	.033*	22.0	7.5	.010**
	Trail B (s)	36.4	13.4	68.1	65.3		52.2	18.0	
	Total (s)	54.1	16.4	97.3	92.5		74.2	22.6	
SDMT	Number Correct	61.7	9.4	46.8	11.6	< .001**	50.0	7.2	< .001**
DFT	Filled Dots	13.1	3.0	9.7	2.8	< .001*	9.9	2.6	< .001**
	Empty Dots	12.6	2.3	10.6	2.3		10.8	2.1	
VFT	Switching	12.4	2.7	7.6	2.4		8.0	2.1	
	Letter	44.3	10.7	37.8	12.0	.032*	40.0	10.7	.071
	Category	48.1	10.1	41.2	9.5		42.5	8.0	
	Category Switching	16.1	2.5	14.1	3.1		14.4	2.8	
CWIT	Total Switching Accuracy	15.4	2.6	13.6	3.3		14.1	2.8	
	Color (s)	25.9	3.7	40.0	28.9	< .001**	32.0	10.5	< .001**
	Word (s)	19.7	2.9	30.4	21.4		24.0	7.8	
	Inhib (s)	43.3	9.5	68.1	34.5		57.3	13.4	
	Inhib/Switch (s)	49.5	7.7	73.6	34.9		63.0	16.0	
Auditory tests									
WRQ	Left % correct	97.8	2.3	97.6	2.4	.778	97.6	2.5	.906
	Right % correct	98.9	1.5	98.6	1.6		98.8	1.5	
WRB+10	% Correct	87.9	4.3	80.8	14.6	.013*	84.1	5.7	.007**
	Left # correct	27.2	1.8	24.4	5.7	.007**	25.9	2.6	.040*
WIN	Right # correct	26.9	2.4	24.1	4.9		25.3	2.2	
	Left SNR threshold	4.2	1.4	6.5	4.4		5.3	2.1	
	Right SNR threshold	4.5	2.0	6.7	4.0		5.8	1.8	
TC	Left % correct	79.5	7.7	66.6	18.7	.001**	71.8	11.2	.007**
	Right % correct	79.6	9.9	68.8	20.8		74.6	12.6	
GIN	Left % correct	68.9	10.2	60.4	12.2	.022*	61.6	11.5	.089
	Right % correct	66.2	9.8	58.0	10.1		59.6	9.0	
SSW	Left gap threshold	5.6	1.8	6.7	2.4		6.5	2.0	
	Right gap threshold	5.9	1.5	7.0	2.0		6.8	1.8	
	RNC errors	0.1	0.3	0.9	1.5	.012*	0.4	0.6	.001**
	RC errors	0.5	0.7	2.8	4.7		1.6	1.8	
	LC errors	1.5	1.5	4.6	6.0		2.9	2.2	
	LNC errors	0.5	0.6	1.2	1.9		0.7	0.9	

Note. Results are shown separately for the mild traumatic brain injury (mTBI) group including all subjects (mTBI ALL) and only those who showed sufficient test effort (mTBI IE excluded). Results of statistical tests are shown for the overall test. (s) denotes time in seconds. IE = insufficient effort; CVLT = California Verbal Learning Test; DS = Digit Span; TMT = Trail-Making Test; SDMT = Symbol Digit Modalities Test; DFT = Design Fluency Test; VFT = Verbal Fluency Test; CWIT = Color-Word Interference Test; WRQ = Word Recognition in Quiet (monaural); WRB+10 = Binaural Word Recognition in Babble; WIN = Words in Noise; SNR = signal-to-noise ratio; TC = Time-Compressed Speech; GIN = Gaps in Noise; SSW = Staggered Spondaic Word Test; RNC = Right Noncompeting; RC = Right Competing; LC = Left Competing; LNC = Left Noncompeting.

^aOverall result of the multivariate analysis of variance test including all subtests, *p* value.

p* ≤ .05. *p* ≤ .01.

speed are well-documented acute consequences of mTBI, with greater controversy regarding the rate of long-term dysfunction (e.g., McInnes et al., 2017; Rabinowitz & Levin, 2014). To investigate the relationship between behavioral auditory test performance following mTBI and cognitive function, a battery of neuropsychological tests chosen to assess these critical domains was administered to each participant. Tests were administered in verbal and/or paper-and-pencil format, with the subject seated at a table across from the examiner in a quiet room. The selection, proper administration, and scoring of all neuropsychological tests were overseen by a neuropsychologist (second

author). Unless otherwise specified, abnormal performance was defined as > 2 *SDs* from the mean scaled score provided in the published norms of each test.

California Verbal Learning Test–Second Edition

The California Verbal Learning Test–Second Edition (CVLT-II; Delis, Kramer, Kaplan, & Ober, 2000) is a widely used memory test designed to assess the ability to learn and remember verbally presented information in both shorter and longer time periods. Two different word lists (Lists A and B) of 16 words each were presented orally, and participants were asked to listen to the entire

list and repeat as many words as they can remember. List A was administered five times in a row (Trials 1–5), followed by a sole presentation of List B. Participants were then asked to remember items from List A again (short free recall). There was then a 20- to 30-min delay during which participants engaged in other tasks and the subjects were asked to remember items from List A one more time (long free recall). Subscores analyzed for this study were the *T* score of Trials 1–5, short free recall score, and long free recall score.

Digit Span Test

The Digit Span (DS) subtest of the Wechsler Adult Intelligence Scale–Fourth Edition (Wechsler, 2008) was administered as a test of attention and working memory. For DS Forward, the subject was read a sequence of numbers and asked to recall the numbers in the same order. For DS Backward, the subject was read a sequence of numbers and asked to recall the numbers in reverse order. The test began with two digit-length sequences and proceeded in longer sequences until two incorrect trials for a sequence are obtained. Scores were obtained for the length of the longest digit sequence forward and backward as well as the total score.

Trail-Making Test

The Trail-Making Test, originally of the Army Individual Test Battery (1944) and subsequently incorporated into the Halstead–Reitan Neuropsychological Test Battery (Reitan & Wolfson, 1985), is a measure of attention, processing speed, and task switching. The test consisted of two parts in which the subject was instructed to correctly connect circles with a pencil line in order by number (Trail A) or by alternating number and letter (e.g., 1-A-2-B; Trail B) as quickly as possible. The score is the total time in seconds needed to complete the task. Normal cutoffs specified by the test are < 40 s for Trail A, < 91 s for Trail B, and a total combined time of < 110 s.

Symbol Digit Modalities Test

The Symbol Digit Modalities Test (Smith, 1982) is a measure of processing speed, attention, and integration abilities. The individual is given a code and asked to write down the correctly matched number for as many abstract symbols on the page as possible in 90 s. The score is the number of correctly coded items completed within the time limit (up to 110).

Delis–Kaplan Executive Function System

The Delis–Kaplan Executive Function System (Delis, Kaplan, & Kramer, 2001) is a nationally standardized set of nine stand-alone tests to evaluate key components of executive functions. Three of the subtests were used in this study are as follows: (a) Design Fluency Test: This test measures cognitive flexibility and fluency in the spatial domain by having participants connect dots with four straight lines to create a series of novel designs in a repeated array of squares. Three squares of practice with examiner-provided feedback were completed prior to the test, and then subjects were given 60 s to complete as many different designs as

possible. Three trials were completed in different conditions of filled dots only, open dots only, and switching between filled and open dots. The number of unique designs completed in each condition in 60 s was scored. (b) Verbal Fluency Test (VFT): This test measures verbal fluency by having the subject produce as many verbal responses as possible in 60 s given a specific starting letter or category (e.g., animals) and by switching between two categories. (c) Color–Word Interference Test (CWIT): This test measures cognitive flexibility, attention, and processing speed using three traditional Stroop trials (color naming, color name reading, and interference) as well as a fourth trial in which the subject switches back and forth between naming the conflicting ink colors and reading the color names. Scoring is based on the number of correct responses in 60 s.

Medical Symptom Validity Test

In order to evaluate whether poor performance on either auditory behavioral or cognitive tests may be due to lack of effort in our study population, the Medical Symptom Validity Test (MSVT; Alberti, Sarchielli, Mazzotta, & Gallai, 2001), a computer-based screening test, was administered to all subjects. The MSVT is a short, simple, memory task in which patients are presented with 10 word pairs representing common objects that are easy to imagine (e.g., French–Fries) over two trials. The test has been shown to discriminate between those making a full effort, those who are malingering or are offering suboptimal effort, and those with genuine memory impairment (Carone, 2008; Green, 2004; Howe, Anderson, Kaufman, Sachs, & Loring, 2007; Merten, Green, Henry, Blaskewitz, & Brockhaus, 2005; Richman et al., 2006). Scores for four conditions were analyzed: immediate recognition, delayed recognition, paired associate, and free recall. Scores of less than 85% for the first three subtests and less than 50% for the Free Recall portion were considered consistent with poor effort or symptom exaggeration.

Behavioral Auditory Test Battery

A battery of behavioral tests of auditory processing tests was administered to evaluate deficits in speech understanding in noise, temporal processing, and dichotic listening. All tests were administered using CD recordings and presented via the GSI-61 audiometer and ER-3A insert phones. Calibration was performed using the recorded calibration tones for each test for each individual presentation. All tests were presented at 50 dB SL with regard to the 0.5-, 1.0-, and 2.0-kHz average or at 60 dB HL as indicated in the descriptions below (which was an equivalent level or within 5 dB for the majority of subjects). Unique word lists were used for each ear and test condition. All behavioral auditory testing was completed in the sound-treated audiometric booth. Instructions were read to and explained to the participants prior to each test. It should be noted that the tests selected for this study do not represent an entire central auditory processing test battery and were not intended to diagnose an auditory processing disorder.

Monaural Word Recognition in Quiet

The monaural word recognition in quiet (WRQ) task was administered as a control for the influence of possible peripheral hearing loss on absolute speech recognition and to compare abilities between groups, with both expected to perform normally on this task. Fifty consonant–vowel–consonant Northwestern University Auditory Test No. 6 (NU-6; Tillman & Carhart, 1966) words were presented separately to each ear at 50 dB SL. A score of 90% or greater was considered normal performance.

Binaural Word Recognition in Babble

A measure of speech understanding in noise under a constant signal-to-noise ratio (SNR) was completed using a set of 50 NU-6 words presented binaurally at +10 dB SNR at 50 dB SL. The primary purpose of this fixed level of speech-in-noise task was to provide a direct behavioral comparison for the electrophysiological task outcomes under the same conditions (presented elsewhere). The background noise was a 20-talker babble prerecorded on the second track of the same CD from Auditec of St. Louis. Based on the range of performance in the control group, the control mean of -2 *SD*, and a comparison to performance–intensity functions for NU-6 words in a multitalker babble from Wilson and Cates (2008), the cutoff for normal performance was 80% correct.

Words in Noise

As difficulty understanding speech in background noise has been a consistent finding in the literature and one of the most commonly reported functional auditory complaints, a more challenging clinical word recognition in noise task with varying SNR was also administered to better evaluate differences across groups and compare to existing literature. The Words in Noise (WIN) Test developed by Wilson and colleagues (Wilson & Burks, 2005; Wilson & McArdle, 2007) and available on CD (Department of Veterans Affairs, 2006) consists of 35 monosyllabic words presented in seven progressively more difficult SNRs. Starting with a signal level of 60 dB HL, five words were presented at each SNR, which decreased in 4-dB increments from +24 to 0 dB. Each ear was tested separately. The WIN Test specifies that normal performance is 25–35 words correct ($\geq 71\%$), with an SNR threshold of ≤ 6.0 dB. For the purposes of this study, we required both criteria to be met, based on several “abnormal” results at 6.8-dB SNR threshold when the number correct was in the normal range equally across both groups ($n = 7$ ears controls, $n = 6$ ears mTBI).

Time-Compressed Speech

Damage to the auditory neural pathway is likely to disrupt encoding of subtle timing in acoustic signals and impair temporal auditory processing abilities. As a measure of ability to understand temporally degraded speech, time-compressed (TC) speech recognition was tested using NU-6 words with carrier phrases (“Say the word ____”) recorded with 65% time compression. Lists were presented at 50 dB SL to each ear separately. Based on data from Wilson, Preece,

Salamon, Sperry, and Bornstein (1994), the cutoff for normal performance was 55.5%.

Gaps in Noise

The Gaps in Noise (GIN) Test (Musiek et al., 2005) was included to assess another aspect of temporal processing—the ability to resolve very brief acoustic silent periods in noise. The GIN Test, developed by Musiek et al. (2005), has been shown to be sensitive to impaired temporal resolution in patients with cortical and brainstem lesions. The test consists of 6-s segments of broadband noise containing zero to three silent gaps with gap durations of 2, 3, 4, 5, 6, 8, 10, 12, 15, and 25 ms randomized within each list for a total of six presentations each. The subject’s task was to press the audiometer response button immediately for each gap/interval detected, and a short practice list was provided for familiarization prior to testing. Each ear was tested separately. The test was scored as both a percent correct and a threshold estimate based on the smallest gap for which greater than 50% detection was obtained with scores greater than 50% for all longer gaps. Abnormal performance was considered a gap threshold greater than 8 ms and a total score of less than 54% in either ear. Again, for the purposes of this study, both criteria were required to be met for abnormal performance.

Staggered Spondaic Word Test

The Staggered Spondaic Word Test (SSW) (Katz & Smith, 1991) is one of the most widely used dichotic listening tasks that assess higher level auditory processing skills involved in integration of binaural auditory information. The SSW has been shown to be sensitive to cortical and corpus callosum involvement (Katz, Basil, & Smith, 1963; Katz & Smith, 1991; Mueller, 1987), which may affect interhemispheric transfer of auditory information. Words with equal emphasis on both syllables (spondees) such as *hotdog* are presented in the format of one per ear, so that the second syllable in one ear and the first syllable in the other ear overlap in time (i.e., competing syllables). Forty test items rotated between right ear first and left ear first presentation. In each case, there were four test conditions scored: right noncompeting syllable, right competing syllable, left competing syllable, and left noncompeting syllable. Subjects were asked to repeat the four syllables/words back in the exact order they heard them presented. The number of errors in each of the competing and noncompeting conditions and the total number of errors were scored and evaluated against SSW norms, which specify the maximum errors for each condition as right noncompeting syllable, right competing syllable, left competing syllable, left noncompeting syllable, and total as 1, 2, 4, 1, and 6, respectively.

Self-Reported Symptoms Questionnaires

Questionnaires were administered to determine the degree of auditory, postconcussion, and psychological/emotional symptoms reported by individual subjects and how these may relate to performance on auditory and cognitive tests.

Functional Hearing Questionnaire

A checklist was administered to rate 12 symptoms commonly associated with auditory processing dysfunction, such as difficulty hearing in background noise, difficulty following oral directions, and difficulty understanding rapid or muffled or rapid speech. This checklist was based on a previously unpublished version (P. Myers, personal communication, January 21, 2011) of what has since been published as the Functional Hearing Questionnaire (FHQ-m; Saunders et al., 2015). Participants were asked to rate each of the 12 items, based on the symptoms they experienced within the last 2 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/reported auditory processing problems).

Rivermead Postconcussion Symptoms Questionnaire

The Rivermead Postconcussion Symptoms Questionnaire (Binder, 1997) is a widely self-report questionnaire consisting of 16 possible postconcussion symptoms. The instructions ask that current symptoms (within the last 24 hr) be compared to remembered preinjury status, and each is rated on a scale of 0–4, with 0 = *no problem at all* to 4 = *a severe problem*. Control subjects were asked to simply rate the severity of any currently experienced symptoms using the same scale. The RPQ includes assessment of three physical symptoms in the first three items (headache, nausea, and dizziness), which are added together to obtain the RPQ3 score (0–12 possible), while the remaining 13 items, such as noise sensitivity, irritability, and poor concentration, are added together separately to obtain the RPQ13 score (0–52 possible). A total score was also calculated as the sum of all 16 questions (total possible score = 0–64).

Beck Depression Inventory–II

The Beck Depression Inventory–II (BDI-II; Beck, Steer, & Brown, 1996) is a self-report inventory of depression symptoms experienced over the past 2 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, which are rated on a scale from 0 (*not at all*) to 3 (*severe*). The total score ranges 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

The Beck Anxiety Inventory (Binder, Rohling, & Larrabee, 1997) 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 and unsteady, having difficulty breathing, and being scared. As in the BDI-II, the total is the sum of each question and ranges from 0 to 63. Clinical interpretation typically uses 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

The Fatigue Severity Scale (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 nine 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.

PTSD Check List–Civilian Version

The PTSD Check List–Civilian Version (Bohnen, Jolles, & Verhey, 1993) is a 17-item questionnaire that asks about symptoms in relation to “stressful experiences” within the past month. Originally developed for the military, this civilian version can be used in any population exposed to traumatic events. The items are based on the *Diagnostic and Statistical Manual of Mental Disorders–Fourth Edition* symptoms of 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) was obtained by summing the scores from each of the 17 items. Scores of 50 or greater are typically interpreted as possible PTSD.

Alcohol Use Disorders Identification Test–Consumption

The Alcohol Use Disorders Identification Test–Consumption (AUDIT-C; Bush, Kivlahan, McDonell, Fihn, & Bradley, 1998) is a brief validated screen for risky drinking and alcohol abuse and dependence (alcohol misuse) consisting of three questions. Recommended screening thresholds have been established as ≥ 4 points for men and ≥ 3 points for women.

Data Analyses

Demographic and audiometric variables were analyzed for balance between groups in terms of mean and standard deviation using *t* tests and analysis of variance (ANOVA), respectively. Group effects for the neuropsychological/cognitive test variables and auditory behavioral test variables were analyzed using a multivariate analysis of variance (MANOVA) model, both including and excluding subjects with insufficient effort (IE). Fisher’s exact test was used to analyze group effects for binary response variables of normal and abnormal test performance as compared to individual test normative cutoffs.

The influence of auditory and emotional/postconcussion symptoms reporting on the behavioral test performance was assessed using correlation and multivariate analysis of covariance. Simple linear regression was conducted for each response variable within each group separately to determine the predictive relationship between symptom scores and behavioral test performance. Logistic analysis was similarly conducted for binary response variables to determine the influence of symptoms on test performance. The dependence of auditory test performance on neuropsychological test performance was assessed using correlation and principal component analyses. Although many of the variables did not satisfy the assumption of normality, the sample size was considered large enough that parametric analyses were completed for all comparisons for consistency and expected to be approximately valid.

Results

As shown in the demographic data in Table 1, each group consisted of 10 males and 22 females. The groups were well balanced in terms of age and years of education, with no significant differences between groups for any of these factors ($p > .05$ for all t tests). Employment status, marital status, and members of household were not statistically analyzed, but distributions among categories were similar for the two groups. The mTBI group members were tested on average of 6 months following injury (range: 3–18 months), and all were being evaluated for or receiving rehabilitation for ongoing symptoms, including physical, cognitive, psychological, and occupational.

The majority of individuals in the mTBI group suffered concussion due to motor vehicle–related accidents (MVA; 38%) or falls (22%), followed by assault (9%), sports-related concussion (9%), and other injuries (22%). Notably, among this group of individuals with mTBI, two thirds had not returned to their previous work or school at the time of the study visits, and another 12% returned at a reduced level or in a sheltered environment. Only six of the 32 reported a full return to work. Similarly, 50% reported they were unable to return to most activities, and another 38% had reduced levels of activity postinjury. Half of the mTBI group reported being involved in some type of injury-related litigation. Details of injury characteristics are available in Supplemental Material S1.

Mean audiograms for the two groups are shown in Figure 1. Recall that participants were excluded if their PTA exceeded 40 dB HL or if there was evidence of middle ear dysfunction. As a result, there were no significant differences between groups at any individual pure-tone frequency or by either regular (0.5, 1.0, and 2.0 kHz) or high-frequency (1.0, 2.0, and 4.0 kHz) PTA by independent-samples t test ($p > .05$ for all t tests). DPOAE SNR were also evaluated between groups at each tested frequency. In most cases, there was no significant difference in DPOAEs; however, the DPOAE SNR was significantly larger for the control group compared to the mTBI group for left ears at two frequencies, 1500 Hz (18.3 vs. 13.6 dB; $t_{62} = 2.323$, $p = .023$) and 8000 Hz (13.4 vs. 7.3 dB; $t_{62} = 2.635$, $p = .011$). These results overall

Figure 1. Mean pure-tone audiometric thresholds (error bars, 1 SD) for the left (top) and right (bottom) ears in each group. The control group is shown with open symbols, and the mild traumatic brain injury (mTBI) group is shown with solid black symbols. Inclusion criteria required the pure-tone average of all participants to have for 1.0, 2.0, and 4.0 kHz no greater than 40 dB HL.

suggest that peripheral hearing status was similar between groups.

Self-Reported Auditory and Postconcussion Symptoms

As part of the case history questionnaire, all participants were asked about symptoms of tinnitus, dizziness, and perceived general communication problems. The FHQ-m questionnaire was used to assess auditory symptoms. Five of the control participants (16%) reported tinnitus, and all rated their tinnitus as “not loud at all” and “not a problem.” In comparison, 21 of the 32 mTBI participants reported tinnitus (66%). Of those, 62% rated their tinnitus as “moderately to extremely loud” and 52% said it was a “moderate to very big problem” (on a scale of *not at all*, *slight*, *moderate*, *big*, *very big*). While two of the control participants reported some dizziness or balance problems, 30 of the 32 (94%) mTBI participants reported problems with dizziness or balance, and 29 of those said the problem began or worsened at the time of injury. In response to a general question “about the effect of their head injury on general satisfaction and effectiveness as a listener,” 88% of the mTBI participants indicated that it had affected them a moderate ($n = 7$), large (10), or very large (11) amount.

The results of the FHQ-m are summarized in Table 3. The mTBI group had a significantly higher total score ($t_{62} = -12.490$, $p < .001$) and significantly higher scores

for each individual question ($p \leq .001$) than the control group. Those with mTBI reported the most problems with hearing in background noise, problems hearing rapid or muffled speech, and sensitivity to loud sounds as evidenced by the highest scores on those items. The mTBI also reported higher scores on items about difficulty memorizing information by listening, difficulty paying attention when people talk, and problems finding words.

The mTBI group generally endorsed a higher number of symptoms on all self-report questionnaires. Effect sizes for the difference in symptoms scores on each questionnaire by group are shown in the left panel of Figure 2, with symbols to the left of the null line representing more symptoms (typically higher scores) for the mTBI group. All symptom scores, except the AUDIT-C (alcohol risk), showed a larger effect for the mTBI group. One-way MANOVA also showed that overall self-report questionnaire scores differed significantly between mTBI and control subjects overall, $F(8, 55) = 56.523$, $p < .001$, $\eta_p^2 = .959$. When the results for each of the questionnaire scores were considered separately, the mTBI group had significantly higher self-report scores than the control group on each of the individual questionnaires ($p \leq .001$, $\eta_p^2 = .39-.83$), except for the AUDIT-C. Results for the AUDIT-C were also significant ($p = .001$, $\eta_p^2 = .16$), but the mean score was higher for the control group compared to the mTBI subjects. That is, individuals with mTBI reported significantly higher symptoms for all auditory, post-concussion, and emotional scales, but the control group reported higher alcohol use. The AUDIT-C results were not considered further.

Scores on other symptom questionnaires were compared to the rate of auditory symptom on the FHQ-m. All comparisons showed significant relationships ($p \leq .001$),

with Pearson correlation coefficients indicating moderately to strongly positive relationships ($r = .57-.79$) between perceived auditory processing problems and general concussion symptoms. The middle and right panels of Figure 2 show example scatter plots of the relationships for the total score of the RPQ, which assesses general concussion symptoms and was the most strongly related to the auditory symptoms ($r = .79$) and the depression symptom score on the BDI-II ($r = .64$). Fatigue scores ($r = .70$) were also strongly associated with increasing auditory symptoms. Scores on the other symptoms questionnaires were more strongly correlated with each other than with the FHQ-m auditory symptoms scores ($r = .66-.88$).

Effort Testing

Because participant effort on neurocognitive testing has been shown to account for a significant portion of the variance in predicting testing outcomes (Green, Rohling, Lees-Haley, & Allen, 2001; Lange, Iverson, Brooks, & Rennison, 2010), it was considered important to consider the influence of effort on all behavioral tests in the current study. Of the 22 mTBI participants, four (12.5%) showed evidence of IE as demonstrated by failure of one or more subtests of the MSVT and the CVLT. All four of these subjects failed multiple subtests of the MSVT and had poor performance on the majority of neuropsychological subtests and auditory behavioral tests. Two additional subjects, one control and one mTBI, fell slightly below criteria on one subtest of the MSVT but performed within normal limits on the CVLT and most other tests. Therefore, these two participants were judged to show sufficient effort. Because

Table 3. Overall mean and standard deviation of scores and responses per question on the Functional Hearing Questionnaire Auditory Symptom questionnaire by group.

Overall score Item analysis	Controls				mTBI			
	M 13	SD 4.5	Range 5–24		M 2.1	SD 2.1	Range 0–8	
	Item score	No (%)	Sometimes (%)	Yes (%)	Item score	No (%)	Sometimes (%)	Yes (%)
1. I have problems hearing and/or understanding in background noise or reverberation (echo/poor acoustics).	9	72	28	0	48	6	38	56
2. I have problems telling where sounds are coming from (localizing).	3	91	9	0	21	50	34	16
3. I have problems understanding rapid speech or muffled speech.	14	56	44	0	45	9	41	50
4. I have problems following spoken instructions.	0	100	0	0	32	25	50	25
5. I have problems discriminating (telling the difference between) one speech sound or word from another.	0	100	0	0	16	59	31	9
6. I am sensitive to loud sounds (bothersome or painful).	17	56	34	9	50	16	13	72
7. I respond inconsistently to sounds or when someone speaks to me (sometimes hear it and other times do not).	2	94	6	0	25	41	41	19
8. I have problems understanding on the phone.	3	91	9	0	18	53	38	9
9. I have problems reading and writing.	0	100	0	0	37	25	34	41
10. I have problems paying attention when people talk to me.	2	94	6	0	46	3	50	47
11. I have difficulty memorizing information learned by listening.	10	69	31	0	47	3	47	50
12. I have problems finding words and expressing myself.	6	81	19	0	41	13	47	41

Note. mTBI = mild traumatic brain injury.

Figure 2. Auditory and postconcussion symptom questionnaire results. The left panel shows the calculated Cohen's *d* effect size, as described for Figure 3. The right two panels show example scatter plots comparing reported symptom scores on the Functional Hearing Questionnaire (FHQ-m) Auditory Symptom questionnaire and the overall Concussion Symptom score on the Rivermead Postconcussion Symptoms Questionnaire (RPQ; center panel) and the Depression score on the Beck Depression Inventory–II (BDI-II; right panel). Pearson correlation coefficient and the best fit regression line are shown in each panel. BAI = Beck Anxiety Inventory; FSS = Fatigue Severity Scale; PCLC = PTSD Check List–Civilian Version; AuditC = Alcohol Use Disorders Identification Test–Consumption.

evaluation of effort is not a typical part of auditory evaluations, we considered the remaining results both including and excluding these subjects to determine how effort failure may influence auditory findings and interpretation.

Neuropsychological Test Results

Raw scores and statistical comparisons for the neuropsychological tests (and each scored subtest) to evaluate cognitive function are shown in the top section of Table 2. For each test, possible group differences for all analyzed subtests were evaluated by MANOVA for two different comparisons: control versus all mTBI subjects and control versus mTBI participants with sufficient effort only (excluding IE subjects). Scores were found to differ between controls and the entire mTBI group for all tests except the CVLT, $F(3, 60) = 1.95, p = .131$. When the IE subjects were excluded, neither the CVLT, $F(3, 56) = 1.09, p = .362$, nor the VFT, $F(4, 55) = 2.29, p = .071$, scores were significantly different between groups, but all other tests remained significantly different by group.

An effect size, Cohen's *d*, was calculated to further examine the group difference in raw scores for all subtests. As shown in the top left panel of Figure 3, Cohen's *d* fell to the right of the null effect line for almost all of the neuropsychological battery subtests, but the 95% confidence interval overlapped 0 for most. In order to compare to the normal range of performance on each test, published cutoff values (typically mean scaled score $\pm 2 SD$), performance for each individual was determined to be normal or abnormal for each test. The top right panel of Figure 3 shows the number of individuals in each group who had abnormal performance by test norms on each subtest for the control group compared to the mTBI group with and without those with IE excluded. When the four subjects with IE were excluded, none of the subtests exceed 15% abnormal performance.

In Figure 4, the overall determination of abnormal performance for the neuropsychological tests as a whole are shown in the top left panel in order of rates of abnormal

performance. If any subtests were abnormal, the entire test was considered abnormal; therefore, for some tests, the abnormal percentage is higher than that shown in Figure 3. The highest percentage of abnormal performance for the mTBI group were for the CVLT and the CWIT. Shown in the bottom right panel is the distribution in terms of number of abnormal tests in the cognitive test battery. The highest number of abnormal scores was for the CWIT, which is a Stroop test. All other tests were passed by all or all but one of the mTBI participants with sufficient effort. All of the non-IE mTBI participants had abnormal performance on at most two tests ($n = 2$), with the majority only having one abnormal test ($n = 5$) or no abnormal cognitive tests ($n = 21$).

Fisher's exact test was used to evaluate the difference in the rate of normal and abnormal test categorizations between the controls and the mTBI groups (all and sufficient effort only). There were no significant difference in the number of normal or abnormal cognitive tests between groups, except for the CWIT, $\chi^2(1) = 6.621, p = .024$, which was no longer significant when the IE subjects were excluded, $\chi^2(1) = 3.609, p = .096$. However, it is important to note that statistics could not be performed for several of the tests where there were no cases of abnormal performance in either group (DS, Symbol Digit Modalities Test, and VFT).

Overall, these results suggest that, although raw scores indicated small but significant reduction in cognitive function for the mTBI group compared to controls across most subtests, there was only a significant difference in the rate of abnormal and normal test performance by normative data in the case of the CWIT and only when the subjects with insufficient test effort were included. When these four subjects were excluded, there were no significant differences in classification of performance, and for several of the tests, there were no abnormal scores at all.

Behavioral Auditory Test Results

Raw scores for the auditory behavioral tests and the scored subtests are shown in the bottom half of Table 2.

Figure 3. Scores for both neuropsychological (top panels) and auditory behavioral (bottom panels) tests. Left panels show Cohen's *d* calculated effect size for each of the scored subtests. Symbols represent effect size, and the lines represent the 95% confidence interval. The solid line down the middle represents the null (no group difference). Bar graphs in the right panels show the percentage of individuals who had abnormal performance on each subtest per the test norms as described in the methods. Open bars represent control participants, whereas solid black bars represent the entire mild traumatic brain injury (mTBI) group, and gray bars represent only those mTBI participants who were judged to have sufficient test effort. IE = insufficient effort; CVLT = California Verbal Learning Test; FR = Free Recall; DS = Digit Span; TMT = Trail-Making Test; SDMT = Symbol Digit Modalities Test; DFT = Design Fluency Test; VFT = Verbal Fluency Test; CWIT = Color-Word Interference Test; WRQ = Word Recognition in Quiet; WRB+10 = Binaural Word Recognition in Babble; WIN = Words in Noise; TC = Time-Compressed Speech; GIN = Gaps in Noise; SSW = Staggered Spondaic Word Test; RNC = Right Noncompeting; RC = Right Competing; LNC = Left Noncompeting; LC = Left Competing.

Figure 4. Overall rates of abnormal performance on each test in the neuropsychological (left panels) and auditory (right panels) test batteries. Bar colors are the same as in the previous figure, and tests are ordered by increasing rates of abnormal performance. Bottom panels show the percentage of participants who had zero, one, two, or more abnormal tests in each of the test batteries. MTBI = mild traumatic brain injury; IE = insufficient effort; DFT = Design Fluency Test; SDMT = Symbol Digit Modalities Test; VFT = Verbal Fluency Test; TMT = Trail-Making Test; CVLT = California Verbal Learning Test; CWIT = Color-Word Interference Test; WR Quiet = Word Recognition in Quiet; WR Bin + 10 = Binaural Word Recognition in Babble; GIN = Gaps in Noise; TC = Time-Compressed Speech; WIN = Words in Noise; SSW = Staggered Spondaic Word Test.

As previously described for the neuropsychological tests, MANOVA tests (except for Binaural Word Recognition in Babble (WRB+10), which had only one subtest) were conducted to evaluate group differences across subtests and tests between controls and either all mTBI participants or those with sufficient effort only. All participants performed well on the WRQ test, and there were no group differences in scores, $F(2, 61) = 0.25, p = .778$. There were significant group differences when comparing controls to the entire mTBI group for the speech recognition in noise tests: WRB+10: $t_{36} = 2.62, p = .013$; WIN: $F(3, 60) = 4.39, p = .007$; TC Speech: $F(2, 61) = 7.29, p = .001$; GIN: $F(4, 59) = 3.10, p = .022$; and SSW: $F(2, 60) = 4.75, p = .012$. When those with IE were excluded, the difference was no longer significant for the GIN, $F(4, 55) = 2.14, p = .089$, but remained significant for the other tests.

Each individual test result was categorized as normal or abnormal based on the criteria described in the Method section. The bottom panels of Figure 3 show the effect size and percent abnormal performance for each group. Effect sizes were again shifted to the right of the null line, indicating better performance for the controls. The 95% confidence interval line overlapped the null for several of the tests, but subscores of the WIN, GIN, and SSW showed significant nonoverlapping results. Comparing the auditory tests (right

bottom panel) to the cognitive tests (top right panel) in Figure 3, it can be seen that there were higher rates of abnormal performance on the auditory battery as a whole. In particular, rates of abnormal performance exceeded 20% in the mTBI group for the subtests of the WIN and SSW. In the right panels of Figure 4, the number of abnormal tests in the auditory battery by percentage of individuals are shown, with the largest percentage of abnormal scores for the WIN and SSW tests, followed by the GIN and TC Speech tests. Nine of the 28 subjects with sufficient effort had abnormal performance on more than one auditory test, with four of these performing abnormally on three or four of the six auditory tests.

Fisher's exact test showed that the number of normal and abnormal tests was significantly different between groups for all tests, except the GIN, $\chi^2(1) = 2.977, p = .130$, and the WRQ (could not be tested) when all mTBI subjects were included. Although the significance levels changed slightly, the same tests still reached significance when the IE subjects were excluded.

In summary, the auditory behavioral test results indicated significant group differences by both raw score and rate of abnormal performance, even when subjects with IE were excluded. Nine of 28 mTBI participants (32%) with sufficient effort had abnormal performance on more than one auditory behavioral test.

Discussion

In response to the growing body of research suggesting that auditory problems are among the wide range of clinical manifestations of mTBI, the current study examined the behavioral cognitive and auditory test performance and symptom reporting in a group of individuals still experiencing any postconcussion symptoms following one incident of mTBI. The key innovations of this research are the use of this relatively homogeneous symptomatic postconcussion population and the control for symptom exaggeration. In contrast to much of the existing literature, including predominantly military/veteran populations (Gallun, Diedesch, et al., 2012; Oleksiak et al., 2015; Saunders et al., 2015), the sample population in this study were civilians with injuries due to MVA, falls, and sports injuries, but no blast-related head injuries were included. Because many individuals spontaneously and quickly recover from concussion without long-term effects, we also attempted to increase homogeneity by limiting the time frame to postacute (not within the first 3 months), but less than 2 years postinjury. Injury demographics in the current study were similar to those reported by Hoover et al. (2017), although their study included multiple mTBIs per participant and a range of 1–46 years following the most recent TBI. Our mean age and age ranges were similar to the Hoover et al. study, but the gender distribution was not reported by the previous study. Turgeon et al. (2011) also included a civilian (sports) population, but included only eight individuals who were between 20 and 29 years old and who had experienced one to five concussions between 1 and 10 years prior.

Auditory and Postconcussion Symptom Reporting

Self-reported hearing difficulty despite normal or near-normal pure-tone thresholds is increasingly recognized in relation to head injury (Gallun, Papesh, & Lewis, 2017; Hoover et al., 2017; Saunders et al., 2015). Per our selection criteria, PTA audiograms did not differ significantly between groups, but not every individual had what would be considered clinically normal hearing at every frequency (< 25 dB HL). There were also significantly poorer DPOAEs for the mTBI group at two frequencies in the left ear. While all behavioral tests were completed at sensation levels that assured audibility, the influence of some amount of peripheral hearing loss and variability in thresholds within the range of normal to mild cannot be ruled out. This limitation of not completely controlling for the influence of peripheral hearing status is shared by previous studies, which have also found small differences in hearing thresholds between groups with and without mTBI (Gallun, Diedesch, et al., 2012) or have recruited control groups specifically to match mTBI groups by age and pure-tone thresholds (Hoover et al., 2017) rather than a typical healthy population.

Self-reported rates of tinnitus (66%) and dizziness (80%) were high among the mTBI participants, although no diagnostic assessment of either was completed for the current study. These numbers are in line with other reports

(including a range of TBI severities and blast injuries and nonblast injuries) that over 80% of those with chronic mTBI experience vestibular problems (Hoffer et al., 2010; Jury & Flynn, 2001; Meehan, Searing, Weaver, & Lewandowski, 2016) and between 48% and 76% report tinnitus (Jury & Flynn, 2001; Oleksiak et al., 2015; Tsao et al., 2017). Thirty-one percent of the mTBI participants rated their tinnitus as a moderate or big problem. Tinnitus associated with trauma, including head trauma and blast injury, has been associated with higher severity levels of distress compared to tinnitus in patients without trauma at tinnitus onset (Folmer & Griest, 2003; Kreuzer et al., 2012; Vernon & Press, 1994).

Despite normal or nearly normal audiograms, individuals in the current study with mTBI self-reported significantly higher rates of symptoms on the FHQ-m. Both the overall score and all per-question scores for the FHQ-m were significantly higher for the mTBI group than for controls, with the most commonly endorsed symptoms being difficulty hearing in noise, sensitivity to loud sound, and difficulty listening to rapid/muffled speech. The mTBI group also scored higher on items that suggested problems with auditory attention and memory (i.e., difficulty memorizing information by listening and problems paying attention when people talk to me). Hoover et al. (2017) found that 84% of their civilian cohort with mTBI reported speech-in-noise difficulty compared to 9% of their matched controls, and Gallun et al. (2016) found 60% of their blast-exposed veteran participants scored as moderate-to-severe hearing handicap despite normal/near-normal hearing thresholds. Saunders et al. (2015) also reported on veterans with blast exposure but included only those with normal or almost normal audiograms who specifically reported auditory difficulties ($n = 99$). Using a later version of the FHQ, they found that problems understanding speech in background noise were the most commonly reported (75% responding mostly or very true), compared to the rates of yes (56%) and sometimes (38%) for the same item in the current study.

Postconcussion Syndrome Symptoms and Effort Testing

It is notable that 66% of our mTBI sample (21 of 32) had not returned to work or school since their injury and 50% (16 of 32) reported being unable to return to most activities. This is in contrast to the overall mTBI literature where the vast majority (91.7%) are reported to have returned to work by 2 months postinjury (Waljas et al., 2014). As a group, they perhaps represented an unusual sample of individuals with multiple postconcussion symptoms and functional impairment, but it is interesting that, among this group, there was a fairly high rate of auditory symptoms and performance deficits on auditory-based tests. A possible link between rates of depression and auditory deficits has previously been noted in service members with mild-moderate TBI (Lange et al., 2014). Whether the likelihood of multiple comorbid emotional/behavioral symptoms such as depression and PTSD increases the probability that individuals will

also perceive auditory deficits or if auditory difficulties contribute to the overall emotional impact is not clear. There is some controversy about whether a chronically impaired subgroup of mTBI even exists in a single uncomplicated mTBI, with some arguing that postconcussion symptoms covary with stress and manifest in reductions in neuropsychological test scores (Rohling et al., 2012). Whether existing as a syndrome or not, the symptoms are multifactorial (cognitive, sensory, emotional) and complex in origin, and the same symptoms may also have different causes in individuals with different injury characteristics. Franke, Czarnota, Ketchum, and Walker (2015) suggest that there may be different clinical subtypes that require distinct treatment pathways. The results of the current study may suggest, for example, a clinical subtype that has auditory functional deficits without significant cognitive dysfunction.

A unique aspect of the current study was the consideration of psychological effort or symptom validity and the influence on all behavioral test results including the auditory test battery. In the field of concussion assessment, validity of neuropsychological test findings is a critical issue, and there has been wide acceptance for the use of symptom validity or effort measures in clinical assessment and research (Heilbronner et al., 2009). The rate of effort failure in this sample of individuals with mTBI and chronic postconcussion problems in the current study was 12.5% (four of 32). This is consistent or slightly lower than rates of about 20%–30% reported in the mTBI literature (Carone, 2008). These four participants performed poorly on multiple tests in the auditory battery (three to five abnormal tests each). Interestingly, one of these participants who failed the effort test only performed abnormally on one of the cognitive tests but three of the auditory tests. Another individual who failed the effort tests performed abnormally on five of the auditory tests and six cognitive tests. It may, therefore, not be obvious beyond a separate effort assessment to know which individuals are performing poorly because of auditory or global deficit versus lack of effort, motivation, or other psychological factors. However, if an individual with concussion performs poorly across the board on auditory tests, audiologists should consider possible influence of either cognitive or psychological factors. In groups with disability or compensation claims, the rate of effort failure has been shown to be even higher, even among those already receiving financial compensation (Green et al., 2001; Larrabee, 2003). In our study sample, half of the participants were involved in some type of injury-related litigation, including worker's compensation and personal injury claims, including three of the four who showed evidence of effort failure.

Neuropsychological and Auditory Behavioral Test Performance

Individuals with mTBI and continued postconcussion problems in this study generally showed performance within the normal range on neuropsychological tests, including those assessing memory, attention, processing speed, and executive function. There were, however, individuals

who performed below the normal range on some of the cognitive tests, and raw scores for the mTBI group as a whole were significantly poorer than for the control group for almost all the cognitive tests. The CVLT, a test of memory and learning, and the CWIT, a Stroop test involving multiple aspects of executive function, had the highest rates of abnormal performance.

Reporting of rates of long-term cognitive impairment after a single mTBI is mixed. It has been generally expected that mild cognitive deficits, primarily in attention, processing speed, memory, and executive functioning, may be present within the acute period (< 30 days) after mTBI but resolve between 1 and 3 months postinjury (Belanger, Curtiss, Demery, Lebowitz, & Vanderploeg, 2005; Carroll et al., 2004; Frencham, Fox, & Maybery, 2005; Schretlen & Shapiro, 2003). However, there is still debate as to whether a subset of individuals experience any chronic or long-term postconcussion cognitive impairment (Bigler et al., 2013; Larrabee, Binder, Rohling, & Ploutz, 2013; Pertab, James, & Bigler, 2009; Rohling et al., 2012). A systematic review by Dikmen et al. (2009) showed clear evidence of long-term cognitive deficits following moderate to severe TBI but failed to find sufficient evidence to determine whether there was an association between a single mTBI and cognitive deficits after 6 months or more. More recent evidence supports the suggestion of possible long-term cognitive deficits and a longer time course (beyond the acute 1- to 3-month period) of cognitive recovery in mTBI, such as a population-based outcomes study in New Zealand tracking 260 adults with mTBI over 1 year postinjury, which demonstrated over 20% of individuals with mTBI were still experiencing cognitive difficulties, particularly with complex attention and memory at 12 months postinjury (Barker-Collo et al., 2015). McInnes et al. (2017) also found that approximately 55% of the participants from reviewed studies who specified first-time concussion (469 of 847) showed evidence of cognitive impairment when pooled across all time points from 3 to > 12 months post-mTBI. While there remains debate, the literature therefore suggests that the concussion/mTBI population is heterogeneous, but a significant proportion of individuals have evidence of long-term cognitive impairment. The findings of our study are in line with this, in that 21% of the mTBI group performed abnormally on neuropsychological measures.

The main purpose of this study was to examine the auditory behavioral test outcomes within the context of this population of individuals with ongoing postconcussion problems. The finding that abnormal performance on auditory behavioral tests exceeded the rate of abnormal performance on cognitive tests is interesting. Significant group differences were found in raw scores across several of the auditory tests, and 32% of the individuals with sufficient effort had abnormal performance on more than one auditory test. There was a significant difference in the rate of abnormal performance between groups, which was not the case for the cognitive tests when the IE subjects were excluded.

In general, evidence from previous studies of auditory outcomes in both military and civilian populations supports

the conclusion from the current study that a subset of individuals experience long-term auditory dysfunction due to mTBI. The highest rates of abnormal performance were on complex tasks requiring more effort and concentration, specifically the SSW and the WIN, representing dichotic listening and speech-in-noise understanding. Although temporal processing of gaps in noise was not significantly different between groups in our study, the mean gap threshold was higher (poorer) and the percent correct was lower for the mTBI group. Another temporal processing task, TC speech, did show significantly poorer performance for the mTBI group by both raw score and percentage of participants with scores considered abnormal. By comparison, Gallun, Diedesch, et al. (2012) found that WRQ was not significantly different from controls in veterans ($n = 36$) with blast exposure, but speech understanding in noise using the Quick Speech-in-Noise Test (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004) and performance on the GIN, masking level differences, and SSW tests were significantly poorer for the blast-exposed group. Seventy-five percent of the blast-exposed participants performed abnormally on at least one test in the central auditory test battery and 44% on two or more tests, compared to 24% and 10% of controls, respectively. Saunders et al. (2015) found that 59% of 99 veterans with blast exposure and normal audiograms performed abnormally on a speech-in-noise test (Hearing in Noise Test; Nilsson, Soli, & Sullivan, 1994), 34% on TC speech, 58% on a measure of gap detection, and 34% on the SSW. They also showed that a smaller percentage of their participants performed abnormally on the cognitive tests in the battery, including the DS test (19%), the Stroop Color and Word Test (Jensen & Rohwer, 1966; 5%), and a story recall working memory test (Woodcock–Johnson Story Recall [Woodcock, McGrew, & Mather, 2001, 2007], 12%). These results are similar to the current study in several ways, including the higher rate of abnormal performance on the auditory behavioral tests than the cognitive evaluations, although the test measures were not the same across studies. Also, in most cases in the Saunders et al. study, performance for individuals was not consistently poor across all tests in the battery, which was true in the current study with the exception of subjects who were found to have IE. In another military study, including participants reporting multiple postconcussive symptoms at least 3 months post their most recent injury, Meehan et al. (2016) found that 58% of their cohort performed abnormally on the SCAN3-A (Keith, 2009) central auditory assessment and $\geq 20\%$ had abnormalities on one or more auditory evoked potentials. However, their sample included 80% who reported at least one blast injury and 73% who reported multiple head injuries. It should also be noted that their study population was 99% male and was notably younger than those in the current study. Similar to the current results, their participants performed well on WRQ and peripheral hearing was generally within normal limits except at 4 and 8 kHz, suggesting limited peripheral involvement.

In the few studies including only civilian, non-blast-exposed populations with mTBI, the general findings are

similar. Although only including eight athletes with one or more sports-related concussions and eight controls without concussion, Turgeon et al. (2011) found that all participants had normal WRQ, but five of the eight athletes with concussion performed abnormally on at least one of the four central auditory tests. The most frequently abnormal was the SSW (four of eight). The athletes were 21–29 years old and all male, and five of the eight had multiple concussions. In another nonmilitary study, Hoover et al. (2017) included 13 participants with mTBI who were at least 1 year out from their most recent injury (range: 1–46 years). At least eight of the 13 had multiple concussions in their history, which were from falls, MVA, and sports. They found no significant group differences on any of their three cognitive measures assessing attention, processing speech, and working memory. Although the mTBI group had a higher proportion of abnormal performance on tests, no significant group differences were found between the matched and mTBI groups on monaural speech-in-noise performance (Quick Speech-in-Noise Test or WIN), binaural spatial release from masking, or on psychophysical tasks of temporal fine structure and spectral resolution.

Conclusions and Clinical Implications

In agreement with the growing body of literature, evidence was found for long-term central auditory dysfunction in a subset of individuals who had chronic postconcussion symptoms after a single mTBI. In contrast to several previous studies, the current study population was a civilian population without the further complication of blast injury, and their single concussion was within a defined time period that did not include the acute phase (within 3 months postinjury) or beyond 18 months postinjury. The participant pool also included a larger percentage of women than most previous studies, which have been dominated by men in the military. The particular population of those with chronic postconcussion problems is the likely target of individuals who should receive audiological evaluation and appropriate intervention based on their results.

It is not surprising that the concussion population in this and other studies is still characterized by heterogeneity and variability given the diversity of injury types and locations as well as individual preinjury factors. Although we attempted to decrease the heterogeneity of our sample with these approaches, conclusions cannot be made about the prevalence of auditory problems in the larger population of all individuals who have experienced concussion in that these participants were self-selected for reporting and seeking treatment. As in other studies, only a subset of the individual with mTBI did more poorly on auditory tests. No single tests were predictive in this study, nor have specific deficits been consistent across studies. In general, more challenging auditory tasks such as speech recognition in noise and dichotic listening appear to be the most difficult.

An individual's overall symptoms and effort are important to consider, and the addition of symptom validity

tests and self-reported psychological symptoms in the current study adds to the knowledge of long-term auditory consequences among the spectrum of postconcussion problems. In general, the more symptoms reported overall, the more auditory problems the individuals identified. It may be important to consider auditory test results in the context of other multidisciplinary assessments and the overall severity of their postconcussion symptoms to avoid mistaking reduced effort for impaired auditory processing. The idea of a “diverse set of pathologies, with associated unique injuries and symptoms, which share a common traumatic origin” (Fakhran & Alhilali, 2014) rather than a specific syndrome may be useful in understanding the relationship of central auditory processing dysfunction in the larger picture of postconcussion problems.

The clinical implications that a subset of individuals can have auditory problems on a long-term basis after concussion are several. First, questions related to past head injury would be appropriate parts of an audiological history in both civilian and military populations. If concussion, head injury, or blast injury is reported, ongoing symptoms common to chronic postconcussion syndrome and central auditory dysfunction should be queried. Further diagnostic exploration of possible central auditory dysfunction should be pursued for individuals who continue to experience multiple symptoms for months and years following their injury, even if they do not specifically express auditory-related problems or show evidence of peripheral hearing loss.

Finally, within the context of a multidisciplinary intervention strategy, rehabilitation intervention based on approaches well known for other populations may be appropriate for those with auditory-based problems after concussion. Management of tinnitus and dizziness/balance problems should be pursued as appropriate using best practice standards. To address evidence for central auditory rehabilitation in this population, Saunders et al. (2018) completed a randomized control trial in blast-exposed veterans with normal/near-normal hearing comparing four common interventions including compensatory communication strategies, personal frequency modulation (FM) systems, and auditory training (AT). Results showed that FM system use was an effective intervention in this population, as evidenced by improved speech understanding in noise scores. AT plus FM use was also effective but did not significantly improve performance over FM alone, nor did AT alone significantly improve performance. Although limited to a blast-exposed veteran population, these results suggest that approaches used in audiology rehabilitation for hearing-in-noise difficulties can be effective strategies for postconcussion auditory problems.

Acknowledgment

This study was funded by National Institute on Deafness and Other Communication Disorders Grant R03 DC010246, awarded to the first author.

References

- Alberti, A., Sarchielli, P., Mazzotta, G., & Gallai, V. (2001). Event-related potentials in posttraumatic headache. *Headache*, 41(6), 579–585.
- American Congress of Rehabilitation Medicine. (1993). American Congress of Rehabilitation Medicine Mild Traumatic Brain Injury Committee of the Head Injury Interdisciplinary Special Interest Group. Definition of mild traumatic brain injury. *Journal of Head Trauma Rehabilitation*, 8(3), 86–87.
- American National Standards Institute. (2010). *Specification for audiometers* (ANSI S3.6-2010). New York, NY: Author.
- Arciniegas, D. B., Anderson, C. A., Topkoff, J., & McAllister, T. W. (2005). Mild traumatic brain injury: A neuropsychiatric approach to diagnosis, evaluation, and treatment. *Neuropsychiatric Disease and Treatment*, 1(4), 311–327.
- Army Individual Test Battery. (1944). *Manual of directions and scoring*. Washington, DC: War Department, Adjutant General's Office.
- Barker-Collo, S., Jones, K., Theadom, A., Starkey, N., Dowell, A., McPherson, K., . . . Group, B. R. (2015). Neuropsychological outcome and its correlates in the first year after adult mild traumatic brain injury: A population-based New Zealand study. *Brain Injury*, 29(13–14), 1604–1616.
- Beck, A. T., Steer, R. A., & Brown, G. K. (1996). *Manual for Beck Depression Inventory-II (BDI-II)*. San Antonio, TX: The Psychological Corporation.
- Belanger, H. G., Curtiss, G., Demery, J. A., Lebowitz, B. K., & Vanderploeg, R. D. (2005). Factors moderating neuropsychological outcomes following mild traumatic brain injury: A meta-analysis. *Journal of the International Neuropsychological Society*, 11(3), 215–227.
- Bergemalm, P. O., & Borg, E. (2001). Long-term objective and subjective audiologic consequences of closed head injury. *Acta Oto-Laryngologica*, 121(6), 724–734.
- Bergemalm, P. O., & Lyxell, B. (2005). Appearances are deceptive? Long-term cognitive and central auditory sequelae from closed head injury. *International Journal of Audiology*, 44(1), 39–49.
- Bigler, E. D. (2014). Effort, symptom validity testing, performance validity testing and traumatic brain injury. *Brain Injury*, 28(13–14), 1623–1638.
- Bigler, E. D., Farrer, T. J., Pertab, J. L., James, K., Petrie, J. A., & Hedges, D. W. (2013). Reaffirmed limitations of meta-analytic methods in the study of mild traumatic brain injury: A response to Rohling et al. *Clinical Neuropsychology*, 27(2), 176–214.
- Binder, L. M. (1997). A review of mild head trauma. Part II: Clinical implications. *Journal of Clinical and Experimental Neuropsychology*, 19(3), 432–457.
- Binder, L. M., Rohling, M. L., & Larrabee, G. J. (1997). A review of mild head trauma. Part I: Meta-analytic review of neuropsychological studies. *Journal of Clinical and Experimental Neuropsychology*, 19(3), 421–431.
- Bohnen, N., Jolles, J., & Verhey, F. R. (1993). Persistent neuropsychological deficits in cervical whiplash patients without direct headstrike. *Acta Neurologica Belgica*, 93(1), 23–31.
- Broglio, S. P., Pontifex, M. B., O'Connor, P., & Hillman, C. H. (2009). The persistent effects of concussion on neuroelectric indices of attention. *Journal of Neurotrauma*, 26(9), 1463–1470.
- Bush, K., Kivlahan, D. R., McDonnell, M. B., Fihn, S. D., & Bradley, K. A. (1998). The AUDIT alcohol consumption questions (AUDIT-C): An effective brief screening test for problem drinking. Ambulatory Care Quality Improvement Project (ACQUIP). Alcohol Use Disorders Identification Test. *Archives of Internal Medicine*, 158(16), 1789–1795.

- Carone, D. A. (2008). Children with moderate/severe brain damage/dysfunction outperform adults with mild-to-no brain damage on the Medical Symptom Validity Test. *Brain Injury*, 22(12), 960–971.
- Carroll, L. J., Cassidy, J. D., Peloso, P. M., Borg, J., von Holst, H., Holm, L., . . . Pepin, M. (2004). Prognosis for mild traumatic brain injury: Results of the WHO Collaborating Centre Task Force on Mild Traumatic Brain Injury. *Journal of Rehabilitation Medicine*, 2004(Suppl. 43), 84–105.
- Centers for Disease Control and Prevention. (2015). *Report to Congress on Traumatic Brain Injury in the United States: Epidemiology and Rehabilitation*. National Center for Injury Prevention and Control; Division of Unintentional Injury Prevention. Atlanta, GA.
- Cubon, V. A., Putukian, M., Boyer, C., & Dettwiler, A. (2011). A diffusion tensor imaging study on the white matter skeleton in individuals with sports-related concussion. *Journal of Neurotrauma*, 28(2), 189–201.
- Davenport, N. D. (2016). The chaos of combat: An overview of challenges in military mild traumatic brain injury research. *Frontiers in Psychiatry*, 7, 85.
- De Beaumont, L., Brisson, B., Lassonde, M., & Jolicoeur, P. (2007). Long-term electrophysiological changes in athletes with a history of multiple concussions. *Brain Injury*, 21(6), 631–644.
- De Beaumont, L., Theoret, H., Mongeon, D., Messier, J., Leclerc, S., Tremblay, S., . . . Lassonde, M. (2009). Brain function decline in healthy retired athletes who sustained their last sports concussion in early adulthood. *Brain*, 132(Pt 3), 695–708.
- Delis, D. C., Kaplan, E., & Kramer, J. H. (2001). *Delis-Kaplan Executive Function System (D-KEFS)*. San Antonio, TX: Pearson.
- Delis, D. C., Kramer, J. H., Kaplan, E., & Ober, B. A. (2000). *California Verbal Learning Test—Second Edition (CVLT-II)*. San Antonio, TX: Pearson.
- Department of Veterans Affairs. (2006). *Speech recognition and identification materials: Disc 4.0* [Computer software]. Mountain Home, TN: Veterans Affairs Medical Center.
- Dikmen, S. S., Corrigan, J. D., Levin, H. S., Machamer, J., Stiers, W., & Weisskopf, M. G. (2009). Cognitive outcome following traumatic brain injury. *Journal of Head Trauma Rehabilitation*, 24(6), 430–438.
- Fakhran, S., & Alhilali, L. (2014). Evolution of MRI of brain injury in concussion patients. *Future Neurology*, 9(5), 517–520.
- Flood, G. M., Dumas, H. M., & Haley, S. M. (2005). Central auditory processing and social functioning following brain injury in children. *Brain Injury*, 19(12), 1019–1026.
- Folmer, R. L., & Griest, S. E. (2003). Chronic tinnitus resulting from head or neck injuries. *Laryngoscope*, 113(5), 821–827.
- Franke, L. M., Czarnota, J. N., Ketchum, J. M., & Walker, W. C. (2015). Factor analysis of persistent postconcussive symptoms within a military sample with blast exposure. *Journal of Head Trauma Rehabilitation*, 30(1), E34–E46.
- Frencham, K. A., Fox, A. M., & Maybery, M. T. (2005). Neuropsychological studies of mild traumatic brain injury: A meta-analytic review of research since 1995. *Journal of Clinical and Experimental Neuropsychology*, 27(3), 334–351.
- Gallun, F. J., Diedesch, A. C., Kubli, L. R., Walden, T. C., Folmer, R. L., Lewis, M. S., . . . Leek, M. R. (2012). Performance on tests of central auditory processing by individuals exposed to high-intensity blasts. *Journal of Rehabilitation Research & Development*, 49(7), 1005–1025.
- Gallun, F. J., Lewis, M. S., Folmer, R. L., Diedesch, A. C., Kubli, L. R., McDermott, D. J., . . . Leek, M. R. (2012). Implications of blast exposure for central auditory function: A review. *Journal of Rehabilitation Research & Development*, 49(7), 1059–1074.
- Gallun, F. J., Lewis, M. S., Folmer, R. L., Hutter, M., Papesh, M. A., Belding, H., & Leek, M. R. (2016). Chronic effects of exposure to high-intensity blasts: Results on tests of central auditory processing. *Journal of Rehabilitation Research & Development*, 53(6), 705–720.
- Gallun, F. J., Papesh, M. A., & Lewis, M. S. (2017). Hearing complaints among veterans following traumatic brain injury. *Brain Injury*, 31(9), 1183–1187.
- Green, P. (2004). *Green's Medical Symptom Validity Test (MSVT). User's manual*. Edmonton, Canada: Green's Publishing.
- Green, P., Rohling, M. L., Lees-Haley, P. R., & Allen, L. M., III. (2001). Effort has a greater effect on test scores than severe brain injury in compensation claimants. *Brain Injury*, 15(12), 1045–1060.
- Heilbronner, R. L., Sweet, J. J., Morgan, J. E., Larrabee, G. J., Millis, S. R., & Conference, P. (2009). American Academy of Clinical Neuropsychology consensus conference statement on the neuropsychological assessment of effort, response bias, and malingering. *Clinical Neuropsychology*, 23(7), 1093–1129.
- Henry, L. C., Tremblay, S., Leclerc, S., Khiat, A., Boulanger, Y., Ellemberg, D., & Lassonde, M. (2011). Metabolic changes in concussed American football players during the acute and chronic post-injury phases. *BMC Neurology*, 11, 105.
- Henry, L. C., Tremblay, J., Tremblay, S., Lee, A., Brun, C., Lepore, N., . . . Lassonde, M. (2011). Acute and chronic changes in diffusivity measures after sports concussion. *Journal of Neurotrauma*, 28(10), 2049–2059.
- Hoffer, M. E., Balaban, C., Gottshall, K., Balough, B. J., Maddox, M. R., & Penta, J. R. (2010). Blast exposure: Vestibular consequences and associated characteristics. *Otology & Neurotology*, 31(2), 232–236.
- Hoover, E. C., Souza, P. E., & Gallun, F. J. (2017). Auditory and cognitive factors associated with speech-in-noise complaints following mild traumatic brain injury. *Journal of the American Academy of Audiology*, 28(4), 325–339.
- Howe, L. L., Anderson, A. M., Kaufman, D. A., Sachs, B. C., & Loring, D. W. (2007). Characterization of the Medical Symptom Validity Test in evaluation of clinically referred memory disorders clinic patients. *Archives of Clinical Neuropsychology*, 22(6), 753–761.
- Jensen, A. R., & Rohwer, W. D., Jr. (1966). The Stroop Color-Word Test: A review. *Acta Psychologica*, 25(1), 36–93.
- Jury, M. A., & Flynn, M. C. (2001). Auditory and vestibular sequelae to traumatic brain injury: A pilot study. *New Zealand Medical Journal*, 114(1134), 286–288.
- Katz, J., Basil, R. A., & Smith, J. M. (1963). A Staggered Spondaic Word Test for detecting central auditory lesions. *Annals of Otology, Rhinology & Laryngology*, 72, 908–917.
- Katz, J., & Smith, P. S. (1991). The Staggered Spondaic Word Test. A ten-minute look at the central nervous system through the ears. *Annals of the New York Academy of Sciences*, 620, 233–251.
- Keith, R. (2009). *SCAN-3: A tests for auditory processing disorders in adolescents and adults*. San Antonio, TX: Pearson.
- Killion, M. C., Niquette, P. A., Gudmundsen, G. I., Revit, L. J., & Banerjee, S. (2004). Development of a quick speech-in-noise test for measuring signal-to-noise ratio loss in normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America*, 116(4, Pt. 1), 2395–2405.
- Kreuzer, P. M., Landgrebe, M., Schecklmann, M., Staudinger, S., Langguth, B., & The TRI Database Study Group. (2012). Trauma-associated tinnitus: Audiological, demographic and clinical characteristics. *PLOS ONE*, 7(9), e45599.
- Krupp, L. B., LaRocca, N. G., Muir-Nash, J., & Steinberg, A. D. (1989). The Fatigue Severity Scale. Application to patients

- with multiple sclerosis and systemic lupus erythematosus. *Archives of Neurology*, 46(10), 1121–1123.
- Lange, R. T., Brickell, T. A., Kennedy, J. E., Bailie, J. M., Sills, C., Asmussen, S., . . . French, L. M.** (2014). Factors influencing postconcussion and posttraumatic stress symptom reporting following military-related concurrent polytrauma and traumatic brain injury. *Archives of Clinical Neuropsychology*, 29(4), 329–347.
- Lange, R. T., Iverson, G. L., Brooks, B. L., & Rennison, V. L.** (2010). Influence of poor effort on self-reported symptoms and neurocognitive test performance following mild traumatic brain injury. *Journal of Clinical and Experimental Neuropsychology*, 32(9), 961–972.
- Larrabee, G. J.** (2003). Detection of malingering using atypical performance patterns on standard neuropsychological tests. *Clinical Neuropsychology*, 17(3), 410–425.
- Larrabee, G. J., Binder, L. M., Rohling, M. L., & Ploetz, D. M.** (2013). Meta-analytic methods and the importance of non-TBI factors related to outcome in mild traumatic brain injury: Response to Bigler et al. (2013). *Clinical Neuropsychology*, 27(2), 215–237.
- McInnes, K., Friesen, C. L., MacKenzie, D. E., Westwood, D. A., & Boe, S. G.** (2017). Mild traumatic brain injury (mTBI) and chronic cognitive impairment: A scoping review. *PLOS ONE*, 12(4), e0174847.
- Meehan, A., Searing, E., Weaver, L. K., & Lewandowski, A.** (2016). Baseline vestibular and auditory findings in a trial of post-concussive syndrome. *Undersea & Hyperbaric Medicine*, 43(5), 567–584.
- Merten, T., Green, P., Henry, M., Blaskewitz, N., & Brockhaus, R.** (2005). Analog validation of German-language symptom validity tests and the influence of coaching. *Archives of Clinical Neuropsychology*, 20(6), 719–726.
- Mittenberg, W., & Strauman, S.** (2000). Diagnosis of mild head injury and the postconcussion syndrome. *Journal of Head Trauma Rehabilitation*, 15(2), 783–791.
- Mueller, H. G.** (1987). The Staggered Spondaic Word Test: Practical use. *Seminars in Hearing*, 8(3), 267–279.
- Musiek, F. E., Shinn, J. B., Jirsa, R., Bamiou, D. E., Baran, J. A., & Zaida, E.** (2005). GIN (gaps-in-noise) test performance in subjects with confirmed central auditory nervous system involvement. *Ear and Hearing*, 26(6), 608–618.
- Nilsson, M., Soli, S. D., & Sullivan, J. A.** (1994). Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. *The Journal of the Acoustical Society of America*, 95(2), 1085–1099.
- Oleksiak, M., Smith, B. M., St. Andre, J. R., Caughlan, C. M., & Steiner, M.** (2015). Audiological issues and hearing loss among Veterans with mild traumatic brain injury. *Journal of Rehabilitation Research & Development*, 49(7), 995–1004.
- Pertab, J. L., James, K. M., & Bigler, E. D.** (2009). Limitations of mild traumatic brain injury meta-analyses. *Brain Injury*, 23(6), 498–508.
- Rabinowitz, A. R., & Levin, H. S.** (2014). Cognitive sequelae of traumatic brain injury. *Psychiatric Clinics of North America*, 37(1), 1–11.
- Reitan, R. M., & Wolfson, D.** (1985). *The Halstead-Reitan Neuropsychological Test Battery: Therapy and clinical interpretation*. Tucson, AZ: Neuropsychological Press.
- Richman, J., Green, P., Gervais, R., Flaro, L., Merten, T., Brockhaus, R., & Ranks, D.** (2006). Objective tests of symptom exaggeration in independent medical examinations. *Journal of Occupational and Environmental Medicine*, 48(3), 303–311.
- Rohling, M. L., Larrabee, G. J., & Millis, S. R.** (2012). The “miserable minority” following mild traumatic brain injury: Who are they and do meta-analyses hide them. *Clinical Neuropsychology*, 26(2), 197–213.
- Saunders, G. H., Frederick, M. T., Arnold, M. L., Silverman, S. C., Chisolm, T. H., & Myers, P. J.** (2015). Auditory difficulties in blast-exposed Veterans with clinically normal hearing. *Journal of Rehabilitation Research & Development*, 52(3), 343–360.
- Saunders, G. H., Frederick, M. T., Arnold, M. L., Silverman, S. C., Chisolm, T. H., & Myers, P. J.** (2018). A randomized controlled trial to evaluate approaches to auditory rehabilitation for blast-exposed veterans with normal or near-normal hearing who report hearing problems in difficult listening situations. *Journal of the American Academy of Audiology*, 29(1), 44–62.
- Schretlen, D. J., & Shapiro, A. M.** (2003). A quantitative review of the effects of traumatic brain injury on cognitive functioning. *International Review of Psychiatry*, 15(4), 341–349.
- Smith, A.** (1982). *Symbol Digit Modalities Test*. Los Angeles, CA: Western Psychological Services.
- Tillman, T., & Carhart, R.** (1966). *An expanded test for speech discrimination utilizing CNC monosyllabic words (Northwestern University Auditory Test No. 6)* (Technical Report No. SAM-TR-66-55), Brooks Air Force Base, TX: USAF School of Aerospace Medicine.
- Tsao, J. W., Stentz, L. A., Rouhanian, M., Howard, R. S., Perry, B. N., Haran, F. J., . . . Sher, K.** (2017). Effect of concussion and blast exposure on symptoms after military deployment. *Neurology*, 89(19), 2010–2016.
- Turgeon, C., Champoux, F., Lepore, F., Leclerc, S., & Ellemberg, D.** (2011). Auditory processing after sport-related concussions. *Ear and Hearing*, 32(5), 667–670.
- Vernon, J. A., & Press, L. S.** (1994). Characteristics of tinnitus induced by head injury. *Archives of Otolaryngology—Head & Neck Surgery*, 120(5), 547–551.
- Waljas, M., Iverson, G. L., Lange, R. T., Liimatainen, S., Hartikainen, K. M., Dastidar, P., . . . Ohman, J.** (2014). Return to work following mild traumatic brain injury. *Journal of Head Trauma Rehabilitation*, 29(5), 443–450.
- Weschler, D.** (2008). *Weschler Adult Intelligence Scale—Fourth Edition*. San Antonio, TX: Pearson.
- Wilson, R. H., & Burks, C. A.** (2005). Use of 35 words for evaluation of hearing loss in signal-to-babble ratio: A clinic protocol. *Journal of Rehabilitation Research & Development*, 42(6), 839–852.
- Wilson, R. H., & Cates, W. B.** (2008). A comparison of two word-recognition tasks in multitalker babble: Speech Recognition in Noise Test (SPRINT) and Words-in-Noise Test (WIN). *Journal of the American Academy of Audiology*, 19(7), 548–556.
- Wilson, R. H., & McArdle, R.** (2007). Intra- and inter-session test, retest reliability of the Words-in-Noise (WIN) test. *Journal of the American Academy of Audiology*, 18(10), 813–825.
- Wilson, R. H., Preece, J. P., Salamon, D. L., Sperry, J. L., & Bornstein, S. P.** (1994). Effects of time compression and time compression plus reverberation on the intelligibility of Northwestern University Auditory Test No. 6. *Journal of the American Academy of Audiology*, 5(4), 269–277.
- Woodcock, R. W., McGrew, K. S., & Mather, N.** (2001, 2007). *Woodcock Johnson III Tests of Achievement*. Rolling Meadows, IL: Riverside Publishing.