Auditory and Cognitive Factors Associated with Speech-in-Noise Complaints following Mild Traumatic Brain Injury

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Abstract

Background: Auditory complaints following mild traumatic brain injury (MTBI) are common, but few studies have addressed the role of auditory temporal processing in speech recognition complaints.

Purpose: In this study, deficits understanding speech in a background of speech noise following MTBI were evaluated with the goal of comparing the relative contributions of auditory and nonauditory factors.

Research Design: A matched-groups design was used in which a group of listeners with a history of MTBI were compared to a group matched in age and pure-tone thresholds, as well as a control group of young listeners with normal hearing (YNH).

Study Sample: Of the 33 listeners who participated in the study, 13 were included in the MTBI group (mean age = 46.7 yr), 11 in the Matched group (mean age = 49 yr), and 9 in the YNH group (mean age = 20.8 yr).

Data Collection and Analysis: Speech-in-noise deficits were evaluated using subjective measures as well as monaural word (Words-in-Noise test) and sentence (Quick Speech-in-Noise test) tasks, and a binaural spatial release task. Performance on these measures was compared to psychophysical tasks that evaluate monaural and binaural temporal fine-structure tasks and spectral resolution. Cognitive measures of attention, processing speed, and working memory were evaluated as possible causes of differences between MTBI and Matched groups that might contribute to speech-in-noise perception deficits.

Results: A high proportion of listeners in the MTBI group reported difficulty understanding speech in noise (84%) compared to the Matched group (9.1%), and listeners who reported difficulty were more likely to have abnormal results on objective measures of speech in noise. No significant group differences were found between the MTBI and Matched listeners on any of the measures reported, but the number of abnormal tests differed across groups. Regression analysis revealed that a combination of auditory and auditory processing factors contributed to monaural speech-in-noise scores, but the benefit of spatial separation was related to a combination of working memory and peripheral auditory factors across all listeners in the study.

Conclusions: The results of this study are consistent with previous findings that a subset of listeners with MTBI has objective auditory deficits. Speech-in-noise performance was related to a combination of auditory and nonauditory factors, confirming the important role of audiology in MTBI rehabilitation. Further research is needed to evaluate the prevalence and causal relationship of auditory deficits following MTBI.

Key Words: auditory processing disorder, hearing impairment, postconcussive syndrome, traumatic brain injury

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Abbreviations: 2C2AFC = two-cue, two-alternative forced choice; ANOVA = analysis of variance; CAPD = central auditory processing disorder; IC = interaural coherence; IPD = interaural phase difference; MTBI = mild traumatic brain injury; PTA = pure-tone average; QuickSIN = Quick Speech-in-Noise test; SD = standard deviation; SNR = signal-to-noise ratio; SRM = spatial release from masking; SRR = spectral ripple reversal; SRT = speech reception thresholds; TBI = traumatic brain injury; TFS = temporal fine structure; TMR = target-to-masker ratio; WIN = Words-in-Noise test; YNH = young listeners with normal pure-tone thresholds

INTRODUCTION

Traumatic brain injury (TBI) affects 1.4 million people in the United States each year (CDC, 2006). An estimated 75% of reported injuries are mild (Finkelstein et al, 2006). Traditionally it was thought that in the majority of mild traumatic brain injury (MTBI) cases, cognitive and neurosensory sequellae were minor and spontaneously recovered, but recent evidence contradicts that viewpoint (Hoffer et al, 2013). Many patients continue to experience symptoms long after an initial recovery period, a disorder called post-concussive syndrome. Many of those individuals report persistent auditory complaints (Cockrell and Gregory, 1992; Bergemalm and Borg, 2001; Jury and Flynn, 2001; Oleksiak et al, 2012). Moreover, while many symptoms tend to improve over time, auditory complaints are the least likely to recover decades after the injury (Hoofien et al, 2001).

The exact nature of auditory complaints is a source of discussion, but a number of studies report deficits in auditory function which persist even in the absence of auditory threshold elevation (Cockrell and Gregory, 1992; Musiek et al, 2004; Nölle et al, 2004; Bergemalm and Lyxell, 2005; Flood et al, 2005; Turgeon et al, 2011; Gallun et al, 2012; Oleksiak et al, 2012; Saunders et al, 2015). It is unclear whether those deficits were due to peripheral auditory, central auditory, or nonauditory cognitive factors. For example, abnormal results on tests of dichotic listening (Turgeon et al, 2011; Gallun et al, 2012; Saunders et al, 2015) can result from corpus callosum damage (Musiek et al, 2004) that is not auditory specific. While the auditory literature presents impaired performance on complex speech tasks as evidence for auditory processing disfunction, the neuropsychology literature uses deficits on complex speech tasks as evidence of various cognitive impairments. Numerous studies have shown long-term deficits in cognitive function after MTBI, including processing speed (e.g., Dean and Sterr, 2013), working memory (e.g., Vanderploeg et al, 2005), attention (e.g., Mangels et al, 2002), and information processing (e.g., O'Jile et al, 2006). No doubt, both cognitive and auditory factors contribute to impaired performance on speech tasks, but few studies have closely examined the auditory system deficits following TBI.

For listeners with a history of MTBI, difficulty understanding speech in noise may be related to degraded temporal fine-structure (TFS) processing. Neurons in the auditory system respond to sound with submillisecond temporal resolution that is an order of magnitude more precise than other sensory systems (Frisina, 2001; Wang, 2007). This precise encoding may be disrupted by diffuse axonal injury and associated demyelination and neuronal loss. Impaired TFS processing may prevent listeners from taking advantage of TFS cues in speech, including benefits from interaural cues that allow spatial segregation of talkers. These deficits may impair speech understanding in complex listening environments. Although existing data on listeners with MTBI suggest their auditory processing is impaired (Bergemalm and Lyxell, 2005; Turgeon et al, 2011), the complex nature of tasks commonly employed in batteries used to screen for central auditory processing disorder (CAPD) is problematic. Specifically, the demonstrated deficits may be related to cognitive factors, such as memory and attention, which are not specific to the auditory domain. It remains unclear whether auditory complaints resulting from MTBI are psychogenic, are a consequence of domain-general cognitive deficits, or are, in fact, due to impairments specific to the auditory system.

Two studies have evaluated the relationship between auditory and cognitive function after TBI. Bergemalm and Lyxell (2005) reported a correlation between cognition (including processing speed, working memory, and information processing) and tests of auditory processing. In that study, auditory test results were combined across distorted (interrupted) speech, clinical psychophysics (interaural phase), and auditory brainstem response amplitudes and latencies. Auditory results were correlated with cognition across TBI and non-TBI matched controls, but the details of the analysis were not reported. Krause and colleagues (2014) reported a significant correlation between speech in two-talker background and standardized measures of processing speed, as well as a correlation between processing speed and subjective assessment of listening effort while performing various speech-in-noise tasks. Both groups consisted of listeners varying in age across a span of 35 yr (18–55), with normal pure-tone thresholds, so the observed correlation may have been related to the effects of aging on both processing speed (Salthouse, 2000) and speech understanding in noise (Humes and Dubno, 2010). Aging, like TBI, is not a monolithic condition with associated auditory and cognitive deficits, but is correlated with deficits in specific domains. By measuring the cognitive correlates directly, their contribution to deficits in the auditory domain can be evaluated. Accordingly, we still lack data regarding whether both auditory and nonauditory factors are directly related to difficulty understanding speech in noise after TBI.

A final issue of interest is the growing body of data which suggests there is a link between MTBI and auditory processing deficits among individuals who experienced MTBI as a result of military combat, predominantly blast exposure (Gallun et al, 2012; Oleksiak et al, 2012; Saunders et al, 2015). A majority of those individuals also experienced acoustic trauma and a high level of long-term noise exposure. At present, there are few similarly complete data sets that can be used to examine the consequences of nonblast MTBI, such as MTBI caused by falls, sports concussions, or motor vehicle collisions. Turgeon and colleagues (2011) tested a small group of college athletes with sports-related concussions, and found that three of five had deficits on two or more tasks taken from a CAPD screening battery, despite normal pure-tone thresholds. Across blast-exposed and nonblast MTBI, some of the nonspeech abilities most commonly found to be impaired are auditory temporal processing and binaural integration, suggesting a possible deficit in ability to process TFS cues. Such deficits, if present, might reasonably be expected to have a downstream impact on speech understanding.

To address these issues, cognition and auditory processing abilities should be carefully measured and their respective relationships to performance on complex speech tasks tested. In the present study, the role of auditory processing in speech-in-noise deficits following MTBI was evaluated using an extensive battery of tests designed to differentiate the relative contributions of peripheral auditory, auditory processing, and nonauditory cognitive factors. Participants were recruited from a community population whose TBIs were uncomplicated by blast exposure and other potential peripheral damage from military service.

METHODS

Participants

Thirty-three listeners participated in the experiment. Participants were divided into three groups based on medical history, age, and pure-tone thresholds. Thirteen listeners (aged 25–71 yr, mean = 46.7 yr) were included in the MTBI group based on a history of uncomplicated MTBI for which the acute recovery was complete and any residual auditory or cognitive deficits were chronic, long-term symptoms. MTBI classification was determined according to Diagnostic and Statistical Manual of Mental Disorders, 5th ed., defined as patient report of an insult to the head resulting in a period of confusion or disorientation, posttraumatic amnesia of any duration, and loss of consciousness less than 30 min (American Psychiatric Association, 2013). Recovery from acute symptoms typically occurs within two months of MTBI, and persistent symptoms, including persistent auditory complaints, beyond two months are considered chronic symptoms (Hall et al, 2005). MTBI group histories are summarized in Table 1. Persistent symptoms, including auditory complaints, were not required for inclusion in the MTBI group.

In addition to the MTBI group, two groups of control listeners were recruited. These groups included individuals with no history of TBI or other neurological disorders. A

Table 1. Audiometric and Traumatic Injury History Data for Individual MTBI Participants

ID	MTBI History	Time Since Most Recent TBI (Years)	Medical Diagnosis	Audiological Care
363	Three falls	2	Yes, treated for lacerations	None
368	Multiple sports	10	No	None
375	MVA	6	Yes, treated for lacerations	Audiogram WNL
389	Three falls	3	Yes, aphasia treated by SLP	None
398	Multiple sports	11	No	None
402	Multiple sports, MVA	17	Yes, treated for lacerations free refer	None
149	Multiple sports, MVA	1	Yes, CT, monitored for possible hemorrhage	Audiogram and CAPD abnormal, hearing aid (left)
427	Multiple sports, MVA	11	Yes, CT, neuropsychological evaluation WNL	Audiogram WNL
438	MVA	14	Yes, treated for lacerations	None
436	MVA	46	Yes, motor and speech treatment	None
441	Fall	2	Yes, neuropsychological evaluation	Hearing screening WNL
448	Sports	2	Yes, CT; memory loss, balance and word retrieval, treatment for PT, OT, SLP	None
356	Multiple sports	15	No	None

Note: CT = computed tomography; MVA = motor vehicle accident; OT = occupational therapy; PT = physical therapy; SLP = speech and language pathology; WNL = within normal limits.

control group consisting of nine young listeners with normal pure-tone thresholds (YNH; aged 18–24 yr, mean = 20.8 yr) was used to establish normal performance across the various measures in the study. To facilitate a matched-groups design, a second control group was recruited on the basis of age and pure-tone thresholds to match the listeners in the MTBI group. This group (Matched) consisted of 11 participants (aged 27–70 yr, mean = 49 yr). Group mean and standard deviation (SD) audiograms are shown in Figure 1. Listeners recruited for the MTBI group represented a broad range of ages and a small range of hearing loss, as shown in Figure 1. Matched group participants were recruited such that there was no significant group difference in pure-tone thresholds or age compared to the MTBI group. This resulted in a Matched group that does not reflect the age and audiometric distribution that would typically be found in a random sample of the population. Accordingly, matched group data should not be interpreted as reflecting the typical healthy population, but rather as an experimental comparison for interpretation of the MTBI results.

Listeners in all groups completed a basic auditory assessment including otoscopy, tympanometry, pure-tone audiometry, speech reception thresholds (SRTs), and word recognition in quiet using the NU-6 word lists presented via compact disk recording (Auditec, Inc., St. Louis, MO). Audiometric data are summarized in Table 2. Listeners with abnormal tympanometry or conductive hearing loss (defined as a gap in pure-tone air- and bone-conduction thresholds >10 dB at two or more frequencies) were excluded from participation (Roup et al, 1998).

Testing was completed in two or three sessions that each lasted no longer than 2 hours. Participants were recruited from the Northwestern University campus, Evanston, IL, area by flyers and word of mouth. Informed consent was obtained before participation and compensation was provided at an hourly rate. Institutional review board approval was obtained for all recruitment, informed consent, and testing materials and procedures.

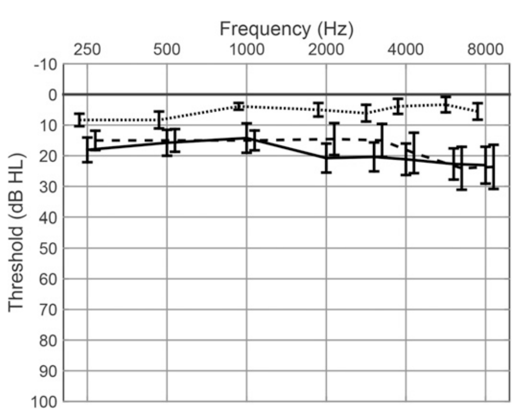

Figure 1. Group mean audiograms for the young, matched, and MTBI groups. The young group is represented by the dotted line, the matched group is represented by the dashed line, and the MTBI group is represented by the solid line. The standard deviation around each point is marked with a vertical bar.

Subjective Impairment

Listeners were asked to subjectively assess their hearing ability using an interview and structured questionnaire. Each listener was asked, "Do you have difficulty understanding speech in a quiet room?" and "Do you have difficulty understanding speech in a noisy room?". In addition to these questions, the short form of the Speech, Spatial, and Qualities of Hearing scale was used to evaluate the perception of sound clarity and quality in various listening situations (Noble et al, 2013).

Speech in Speech Background

Monaural Speech in Multitalker Background

Monaural speech recognition in a background of multitalker noise was evaluated using clinical measures of speech-in-noise deficits. The purpose of this testing was to evaluate (a) a possible group difference in speech-in-noise abilities between the MTBI and Matched groups and (b) whether individual listeners' reported difficulty understanding speech in noise was consistent with signal-to-noise ratio (SNR) loss on tests with known psychometric properties.

Sentence recognition in four-talker noise was measured using the Quick Speech-in-Noise test (QuickSIN; Etymotic Research, Elk Grove Village, IL). The QuickSIN consists of lists of six low-context sentences spoken by a female talker in a background of four-talker babble with a descending SNR. Each listener completed two test lists monaurally in each ear from the reduced set of lists shown to estimate SNR loss consistently in normal and impaired listeners (McArdle and Wilson, 2006).

Word recognition in four-talker noise was evaluated using the Words-in-Noise test (WIN; Wilson and Burks, 2005). WIN words and a preceding carrier phrase are spoken by a male talker in a background of four-talker babble with a descending SNR. Listeners completed one list of 35 words monaurally in each ear. Both the QuickSIN and WIN are scored by the number of key words correctly repeated by the listener. This score is converted to an SNR loss score by calculating the increase in signal relative to the noise that would be necessary for the listener to perform comparably to the YNH group. Details of the physical test environment remained consistent across auditory tasks and are described below.

Binaural Speech in Two-Talker Background

To evaluate listeners' ability to benefit from spatial separation of sound sources (spatial release from masking [SRM]), a measure developed by Gallun and

Table 2. Summary Characteristics for the Young Group, and Individual Matched and MTBI Data

ID	Marker	Age	Difficulty … in quiet?	Difficulty … in nose?	PTA (dB HL)	SRT (dB HL)	WR (%)	QSIN (dB SNR)	WIN (dB SNR)	Spatial Benefit	Abnormal Test	Attention	Processing Speed	Working Memory
Young		18 to 24 (20.8)	0% yes, 100% no	0% yes, 100% no	−2 to 17 (6.4)	−5 to 15 (4.7)	92 to 100 (97)	−0.25 to 4.5 (1.03)	2 to 5.6 (4.5)	2.0 to 10 (6.75)	0 to 3 (1.2)	−1.2 to 1.5 (0)	−1.3 to 1.7 (0)	−2.1 to 1.2 (0)
Match		27 to 70 (49.0)	0% yes, 100% no	9% yes, 91% no	0 to 50 (15.2)	0 to 45 (13.2)	73 to 100 (95)	−2.25 to 11 (2.18)	3.6 to 14.8 (6.5)	1.0 to 9.0 (6.55)	0 to 8 (2.2)	−1.1 to 1.6 (0.0)	−6.5 to 0.2 (−2.5)	−2.1 to 1.1 (−0.2)
9	★	38	No	No	12/8	10/5	100/96	2.0/3.0	5.2/5.2	7.5	1	0.31	−2.57	0.04
364	+	63	No	No	13/13	10/10	96/96	1.5/5.0	2.0/6.0	6	3	0.45	−6.48	−0.13
377	o	65	No	No	17/13	15/15	92/100	3.0/3.5	6.0/4.4	7.5	3	−0.59	−2.17	−0.13
382	●	56	No	No	18/15	15/10	96/96	0.0/0.0	**7.6**/3.6	6	3	−0.22	−2.17	−0.57
290	×	35	No	No	2/3	0/0	100/100	−1.5/−3.0	**6.8**/6.0	7	1	1.61	−2.17	−2.13
95	□	46	No	No	8/3	5/5	96/100	0.0/−2.0	4.4/2.8	9	0	1.15	−1.39	0.73
453	◇	46	No	No	18/15	10/10	100/96	0.5/1.0	3.6/6.0	8	0	−0.08	−1.00	1.08
354	∆	27	No	No	0/3	0/10	100/100	2.5/2.5	**7.6**/5.2	7.5	1	−0.56	0.17	0.04
361	▽	28	No	No	10/17	10/15	96/96	1.5/2.0	6.0/**6.8**	1	2	−0.60	−2.96	−0.74
324	▷	70	No	Yes	**45/50**	**40/45**	**70/76**	**10.0/12.0**	**13.2/16.4**	2	7	−1.09	−3.35	−0.22
270	◁	65	No	No	**30**/22	**30/20**	92/100	0.5/4.0	**8.4/10.0**	5	2	−0.14	−2.96	−0.05
MTBI		25 to 71 (46.7)	0% yes, 100% no	85% yes, 15% no	−2 to 50 (15.8)	0 to 30 (14.2)	76 to 100 (95)	0.25 to 7.75 (2.62)	3.2 to 14.4 (7.7)	−1.5 to 10.5 (3.92)	0 to 8 (3.2)	−0.7 to 1.2 (0.0)	−6.5–0.6 (−3.1)	−1.3 to 0.8 (−0.3)
363	★	60	No	Yes	3/5	5/10	92/100	1.0/5.0	5.2/6.0	2.5	2	0.09	−3.35	−0.48
368	+	32	No	Yes	5/5	5/5	96/96	2.0/0.0	6.0/5.2	8	0	−0.01	−1.39	0.30
375	O	26	No	Yes	5/12	5/5	100/100	0.0/3.0	**6.8/9.2**	5	2	−0.67	−0.61	0.13
389	●	62	No	Yes	**25/33**	**20/35**	100/100	1.5/1.5	**7.6**/6.0	−0.5	3	0.64	−4.13	−0.57
398	×	28	No	No	7/3	0/0	96/100	0.0/0.5	5.2/4.4	9	0	−0.37	−2.17	0.30
402	□	34	No	No	3/−2	5/5	100/100	1.0/1.5	3.6/2.8	10.5	0	−0.67	−2.17	0.82
149	◇	25	No	Yes	10/12	15/15	96/92	**5.0/5.0**	**8.4**/2.8	5.5	4	0.20	−1.78	0.38
427	∆	56	No	Yes	5/7	5/10	100/88	**4.0**/2.0	**10.0/9.2**	2	7	−0.45	−2.57	−0.74
438	▽	51	No	Yes	23/**40**	15/**35**	100/92	1.0/4.5	**11.6/17.2**	2	7	−0.73	−2.57	−0.22
436	▷	69	No	Yes	20/17	20/15	96/96	**4.0/4.5**	**6.8/11.6**	3	4	0.85	−5.70	−1.26
441	◁	52	No	Yes	**47/50**	**25/35**	**80/72**	**9.0/6.5**	**14.0/13.2**	−1.5	6	0.25	−6.48	−0.91
448	☆	71	No	Yes	15/15	15/15	92/96	1.5/2.0	**9.2/6.8**	0.5	4	−0.31	−4.52	−0.74
356	✡	41	No	Yes	23/23	**25/25**	100/96	1.0/1.0	6.0/4.4	5	0	1.15	−3.35	−0.39

Notes: Values in boldface type indicate abnormal results relative to published normative data. Group data are the range and mean. PTA, SRT, WR, QSIN, and WIN individual data are right and left ear monaural scores. Marker symbols correspond to individual data in Figures 2–5. WR = word recognition in quiet.

colleagues (2013) was used. The SRM test consists of three structured sentences presented simultaneously in a spatial environment simulated with headphones. Sentences were from the coordinate-response measure corpus (Bolia et al, 2000), matching the formula, "ready <call sign>, go to <color> <number> now," where <call sign> was a label indicating the target sentence and the listener must identify the matching <color> <number> on a response grid. Male talkers were used and the target was always identified by the call sign, "Charlie." The target was located at 0° azimuth in all conditions and the masker talkers were either collocated or spatially separated at ±45° azimuth. Previous results showed that the difference between collocated and ±45° spatial separation was most sensitive to group differences in age and hearing loss (Gallun et al, 2013).

Presentation of the SRM task through headphones (ER2; Etymotic Research) required combining target and masker signals after convolution with a generic head-related impulse response that preserved interaural timing cues, but obscured interaural level cues dependent on individual listener head and pinna morphology. The target talker was presented at a fixed level of 50 dB sensation level relative to the listener's SRTs, and the target-to-masker ratio (TMR) of the maskers was varied in 2-dB increments from −10 to +10 dB TMR. Each listener completed two sets of 20 practice trials in the collocated and spatially separated conditions, which were presented in descending order of TMR. The test included two sets of 20 test trials in the collocated condition, presented in random order of TMR, followed by two sets of 20 trials in the spatially separated condition in random order of TMR. Spatial release was defined as the difference in 50% TMR between collocated and spatially separated conditions expressed in dB. The score represents the benefit the listener received from the virtual spatial separation of the talkers, relying primarily on temporal interaural cues.

Psychophysics

Monaural TFS Difference Limen

Monaural TFS perception was evaluated using methods derived from Moore and Sek (2009). In this task, listeners were presented with a sequence of tones consisting of a harmonic complex with a missing fundamental composed of the tenth through nineteenth harmonic of a 100 Hz fundamental. The target interval contained a shift in the frequency of each harmonic by a fixed frequency, resulting in inconsistent envelope and fine structure information in the signal. The temporal envelope cue derived from the spacing of harmonics remained unchanged, but the TFS and place-pitch cue indicated a deviation from the standard (Oxenham et al, 2009). The tone complexes were presented at 65 dB SPL, and a threshold equalizing noise was presented at −15 dB relative to the tone complex. Stimuli were 400-msec duration including a 25-msec raised-cosine ramp at onset and offset. A random starting phase for each tone in the complex was selected each trial. Threshold for the detection of an increment in frequency was tracked using a two-down, one-up procedure for ten reversals (Levitt, 1971). The last four reversals were averaged to compute threshold. Listeners completed at least one familiarization track and test tracks were completed until performance stabilized. The reported threshold was the average of the best two tracks completed by each listener. Testing was completed monaurally in the right ear using ER-3A headphones (Etymotic Research). A two-cue, two-alternative forced-choice (2C2AFC; Bernstein and Trahiotis, 1982) method was used to reduce the memory load of the psychophysical procedure by presenting the standard before and after each target.

Monaural Spectral Ripple Reversal Detection

Spectral ripple reversal (SRR) detection was used as a gross measure of auditory spectral resolution (Won et al, 2007). A relationship between spectral resolution and speech-in-noise deficits after MTBI could provide evidence of a peripheral rather than a central cause. Stimuli were generated using a bank of sinusoids with 16 Hz spacing and random phase between 350 to 6000 Hz. Sinusoidal spectral modulation was applied on a log-frequency axis. The signal duration was 500 msec and included 50-msec raised-cosine onset and offset ramps. The task was a three-alternative forced-choice task in which the target interval was spectrally modulated with a phase difference of 180° compared to the standard. The spectral modulation rate (expressed as number of ripple periods in one octave) was varied to find the highest rate at which the listener could detect a reversal. Thresholds were tracked to 70.7% correct (Levitt, 1971). Tracks consisted of 14 reversals, with the last 4 reversals averaged to compute thresholds. Presentation level was set at "loud but comfortable" using the Contour Test (Cox et al, 1997), a loudness judgment task in which listeners rated the loudness of ascending intensity noise stimuli. During the SRR test, the presentation level of each signal was roved ±6 dB. Listeners completed two tracks, with additional tracks added if the thresholds were not in agreement. Thresholds from the best two tracks were averaged to give the final threshold score.

Interaural Phase Difference Detection

Low-frequency TFS was evaluated by measuring detection thresholds for a difference in interaural phase in a 500-Hz tone presented to each ear (Hopkins and Moore, 2010). Bergemalm and Lyxell (2005) used a clinical interaural phase difference (IPD) task with 500-Hz stimuli to demonstrate central auditory dysfunction following TBI.

In this task, tones were presented via ER-3A headphones at a root-mean-square level of 80 dB SPL. In the standard interval, the relative phase of the tones was 0°, and the phase difference was varied in the target interval. A two-down, one-up adaptive tracking procedure was used to estimate threshold in a 2C2AFC task. Each interval had a duration of 400 msec, including a 25-msec raised-cosine envelope at onset and offset. Listeners completed at least one familiarization track and repeated tracks until performance stabilized. Each track consisted of ten reversals, of which the final four were averaged to determine threshold. The best two thresholds were averaged to obtain each listener's final threshold.

Interaural Coherence

Detection thresholds for a decrease in interaural coherence (IC) were measured to assess temporal coding in the auditory system (Whitmer et al, 2012). Two independent white-noise sources were added and subtracted with variable weighting factors to generate stimuli for the right and left ears with a given IC (Hartmann and Cho, 2011). The standard interval had a fixed IC of unity. IC in the target interval was adaptively decreased in a two-down, one-up track to estimate threshold. A 2C2AFC task was used. Stimuli were presented over ER-3A headphones at a root-mean-square level of 65 dB SPL. Each interval had a duration of 400 msec, including a 25-msec ramp. The bandwidth of the noise stimuli was 22 kHz, but the signal was attenuated >4 kHz at −20 dB per octave by the headphone frequency response.

Familiarization consisted of at least one track followed by two or more test tracks. Due to the difficulty that many listeners had performing the IC task, a demonstration program was made available for listeners whose tracks failed to converge after two attempts. The demonstration included a switch to turn on and off a 400-msec gated noise signal and a slider controlling IC. Tracks consisted of ten reversals, and the final four reversals were averaged to give a threshold. Listeners' best two track thresholds were averaged to give their reported threshold.

Test Environment

Auditory tests were performed in a double-walled, sound-attenuating booth. Listeners were seated at a table with a computer monitor, keyboard, and mouse. Tests were implemented in MATLAB (Mathworks, Natick, MA) and Pure Data (Puckette, 1996).

Cognition

Cognitive ability was assessed with three tasks measuring attention, processing speed, and working memory. The primary goal of cognitive testing was to rule out differences in cognition between the Matched group listeners, who reported no history of head injury, and those in the MTBI group, who may have suffered global cognitive deficits resulting from their injury. Tests were selected to assess cognition using the visual modality to determine the relationship between nonauditory cognitive factors and the auditory abilities evaluated in this study. The Trail Making Test evaluated executive attention by timing the participants in the completion of a task requiring them to mark consecutive circles labeled numerically or with alternating numbers and letters (Reitan, 1958). A digit-symbol coding task evaluated processing speed by timing the participants in a symbol-coding task completed using a paper and pencil (Wechsler, 1945). A computer-based reading span test was used to evaluate visual working memory, in which participants were asked to recall key words while reading and evaluating the semantic validity of unrelated sentences (Shah and Miyake, 1996).

Statistical Analyses

Matched-Groups Design

A matched-groups design was adopted in this study to evaluate potential group differences in auditory processing. Given that little is known about the long-term effects of TBI on the perception of basic auditory cues, and that a recent study cast doubt on the idea that TBI results in impaired speech understanding in noise (Krause et al, 2014), the present study was designed to explore the role of auditory and cognitive processes affecting speech. Aging, as well as age-typical elevation in pure-tone thresholds, is known to affect speech understanding in noise, which is mediated by a combination of auditory and cognitive factors. In this study, listeners with a history of TBI were recruited across a wide range of ages and an age-typical range of pure-tone thresholds. By comparing this group to a matched group of listeners with no history of neurological insult, but which spans an equivalent range of ages and pure-tone thresholds, any specific deficit resulting from TBI, but not age or pure-tone threshold, could be demonstrated. The number of abnormal test results for listeners in the TBI group is often reported in studies that include a battery of auditory tests (Nölle et al, 2004; Bergemalm and Lyxell, 2005; Turgeon et al, 2011; Gallun et al, 2012; Saunders et al, 2015). In this study, the number of listeners with abnormal results was computed based on normative data when available, and based on YNH group data otherwise. The purpose of counting abnormal results is to compare the rate of abnormal results between MTBI and Matched groups, and to facilitate comparison with previous reports.

Statistical Methods

Group comparisons presented in this study include repeated measures analysis of variance (ANOVA) in which three groups are compared (MTBI, YNH, and Matched) across within-participants factors of speech-in-noise performance, auditory processing, and cognition. To evaluate the role of auditory and cognitive factors in deficits understanding speech in noise, stepwise linear regression was used, including auditory and cognitive predictors of speech-in-noise performance.

RESULTS

Auditory and Cognitive Measures

Subjective Impairment

Each participant was asked if they had difficulty understanding speech in a quiet or noisy room. In the young group, all of the listeners responded "no" to both questions. None of the listeners in the Matched group responded that they had difficulty in quiet, but one (1/11) said they had difficulty in noise. This listener had audiometry consistent with mild-to-moderate sensorineural hearing loss. Two other listeners in the Matched group had borderline or mild sensorineural hearing loss, but denied difficulty in noise. In the MTBI group, all of the listeners answered "no" when asked about difficulty in quiet, but 11 (11/13) answered "yes" to difficulty in noise. Details about individual listener responses in the MTBI group are listed in Table 2.

Speech in Speech Background

The QuickSIN and WIN were used to evaluate potential MTBI group differences in monaural speech understanding. Figure 2A shows the QuickSIN and Figure 2B shows the WIN mean and SD for the three groups in each ear, as well as individual participant data, with a horizontal line representing the cutoff for normal performance. Individual data for the MTBI group are listed alongside audiometric data in Table 2. In the YNH group, one listener (1/9) performed outside of the normal range of 3 dB SNR loss on the QuickSIN in both ears. Four listeners (4/11) were outside of the normal range in the Matched group in at least one ear, and six (6/13) listeners were outside of normal in the MTBI group in at least one ear. On the WIN, none of the listeners in the YNH group tested outside of the normal range of 6.6 dB SNR loss in either ear. Six in the Matched group (6/9) and eight in the MTBI group (8/13) were outside of the normal range in at least one ear on the WIN.

Continuous QuickSIN and WIN thresholds for each participant were compared via ANOVA to evaluate potential group differences using a within-participants factor of SNR loss score and a between-participants factor of group. A significant effect of group was found for WIN SNR loss score in the left ear only [$F_{(2,23.436)} = 3.491$, $p = 0.043$, $\eta_p^2 = 0.189$]. Post hoc tests of group mean differences for WIN left ear threshold showed that the YNH group mean SNR loss was significantly better than the MTBI group (mean difference = −2.968 dB, $p = 0.013$), but not the Matched group ($p = 0.159$); no difference was found between the Matched and MTBI groups ($p = 0.235$). This finding is consistent with the fact that the groups contain predominantly normal-hearing listeners, but the Matched and MTBI group mean audiograms were slightly elevated relative to the YNH group.

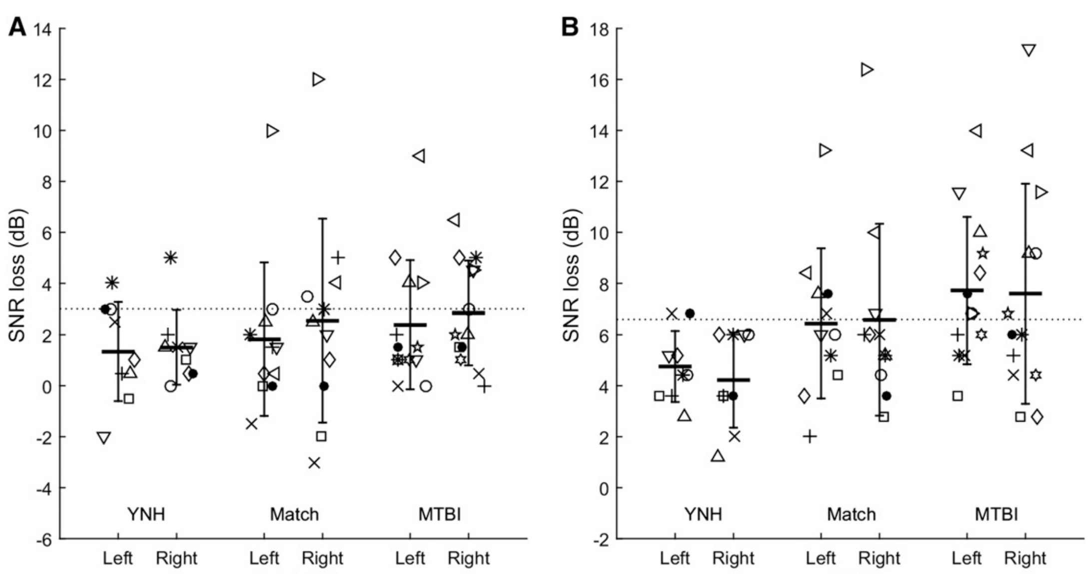

Figure 2. Individual thresholds for the speech-in-noise tests for young, matched, and MTBI group listeners. Listeners in each group are represented by a unique symbol. For the Match and MTBI groups, symbols correspond to those in Table 1. Horizontal bars represent group means and error bars represent the standard deviation. The horizontal dashed line represents the cutoff above which speech recognition in noise is considered abnormal in each test.

Previous reports of listeners with a history of TBI did not find differences relative to controls on speech tasks with collocated, multitalker background (Bergemalm and Lyxell, 2005; Krause et al, 2014).

The ability of listeners to benefit from spatial separation of target and masker talkers was evaluated using the SRM. Individual and group mean SRM data are shown in Figure 3. Scores from the collocated and spatially separated conditions are shown separately and the difference is shown as the benefit of spatial separation. The YNH group mean and SD thresholds were 1.78 (SD = 0.87) dB in the collocated condition and −4.44 (2.60) dB in the spatially separated condition, with a benefit of spatial separation of 6.22 (SD = 2.68) dB. These results are consistent with previous results for young listeners with normal pure-tone thresholds (Gallun et al, 2013). Using YNH data to define normal performance as the mean plus two SDs, the number of Matched and MTBI group listeners with performance outside the normal range was counted. In the Matched group, three listeners in the collocated condition and an additional listener in the spatially separated condition had abnormal results (4/11), but none in the Matched group showed an impaired benefit of spatial separation. In the MTBI group, one listener in the collocated condition and three listeners in the spatially separated condition were outside of the normal range (4/13), and three of these listeners had reduced benefit of spatial separation based on YNH group norms.

A two-way ANOVA was performed to evaluate the benefit of spatial separation on the SRM task and to determine group differences in spatial benefit. Within-subjects factors of collocated and spatially separated performance, a between-subjects factor of group, and group-by-spatial separation interaction were included in the model. A significant effect of spatial separation was found [$F_{(1,7.821)} = 10.707$, $p = 0.003$, $\eta_p^2 = 0.284$] indicating that listeners were able to benefit from the spatial separation of the talkers. Group differences were not statistically significant [$F_{(2,2.188)} = 2.996$, $p = 0.067$, $\eta_p^2 = 0.182$], nor was the interaction of group and spatial separation [$F_{(2,1.420)} = 1.944$, $p = 0.163$, $\eta_p^2 = 0.126$]. This is consistent with previous studies that found no group effects comparing listeners with TBI to age-matched peers on complex auditory tasks (Bergemalm and Lyxell, 2005). However, these data are also consistent with the finding that impairments are often very heterogeneous across individuals, rather than consisting of a common deficit shown by all group members (Gallun et al, 2012). For this reason, individual patterns of impairment may be more indicative of the types of dysfunction observed clinically than group differences.

To evaluate whether subjective claims of difficulty in noise were supported by objective speech-in-noise scores, a repeated measures ANOVA was performed on the pooled data from the MTBI and Matched groups, with a between-subjects factor of stated speech-in-noise deficit (as defined by listener responses to the question regarding difficulty understanding speech in noise) and within-subjects factors of the QuickSIN, WIN, SRM collocated, and SRM spatial-separated scores. A small but significant effect of stated speech-in-noise deficit was found [$F_{(1,14.716)} = 7.270$, $p = 0.013$, $\eta_p^2 = 0.248$], as well as a significant interaction between stated deficit and speech score [$F_{(3,4.263)} = 3.345$, $p = 0.024$, $\eta_p^2 = 0.132$].

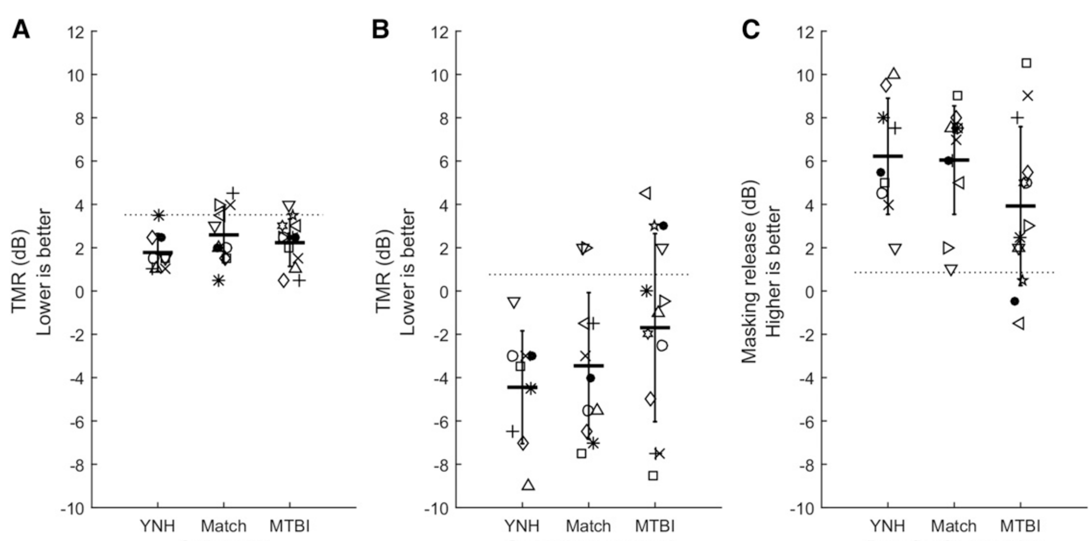

Figure 3. Individual results for the SRM task presented in (A) collocated and (B) spatially separated noise conditions. Each point represents the dB target to masker ratio at the listeners' estimated 50% threshold. The benefit of spatial separation in dB is shown in (C). Listeners in each group are represented by a unique symbol, and the symbols correspond to those used in Table 1. Group mean scores are shown with horizontal bars and vertical bars show the SD. The dashed line represents the cutoff for abnormal performance as defined by 2 SD worse than the YNH mean.

This result shows that listeners in the MTBI group who reported difficulty understanding speech in noise (11/13), combined with the single listener who reported difficulty in the Matched group (1/9), performed significantly worse on objective measures of speech understanding compared to those who reported no difficulty. This finding, along with the finding that several members of the MTBI group have reduced SRM, is consistent with the idea that not all cases of MTBI result in long-term auditory symptoms, but objective deficits are more common among those who report symptoms.

Psychophysics

A repeated measures ANOVA was used to evaluate the between-subjects factor of group across the within-subjects factors of the psychophysical tasks. Greenhouse–Geisser correction of the degrees of freedom and mean squared error was used, due to violation of the sphericity assumption. A significant effect of task [$F_{(1.457,2,504.396)} = 8.419$, $p = 0.002$, $\eta_p^2 = 0.245$] was found, but no significant group difference or group-and-task interaction was observed. For each task, YNH mean and SD performance was calculated and compared to existing studies, and the number of Matched and MTBI group listeners falling outside the mean plus 2 SDs was counted.

Mean and SD TFS thresholds for the YNH group were 9.02 (SD = 5.15) Hz. This is consistent with thresholds obtained using similar stimuli for young listeners with normal pure-tone thresholds (Moore et al, 2006). Two listeners (2/11) in the Matched group and seven listeners (7/13) in the MTBI group had thresholds outside of the normal range. This supports the finding that, in blast-related auditory processing dysfunction (Gallun et al, 2012), group differences may be small or nonexistent, even when substantial numbers of participants perform outside the normal range. Individual and group mean and SD TFS thresholds are shown in Figure 4A. Horizontal lines indicate normal performance based on YNH scores.

SRR thresholds were reported in terms of the number of cycles of spectral modulation per octave, with higher numbers indicating better performance (Figure 4B). Mean and SD SRR thresholds for the YNH group were 4.35 (SD = 1.35) cycles per octave. Thresholds were consistent with previously reported results from young listeners with normal pure-tone thresholds who were tested using the same paradigm (Souza et al, 2014). Thresholds could not be obtained for one listener in the YNH group, reducing the total number of participants included in YNH group to eight. Two listeners (2/11) in the Matched group and three listeners (3/13)

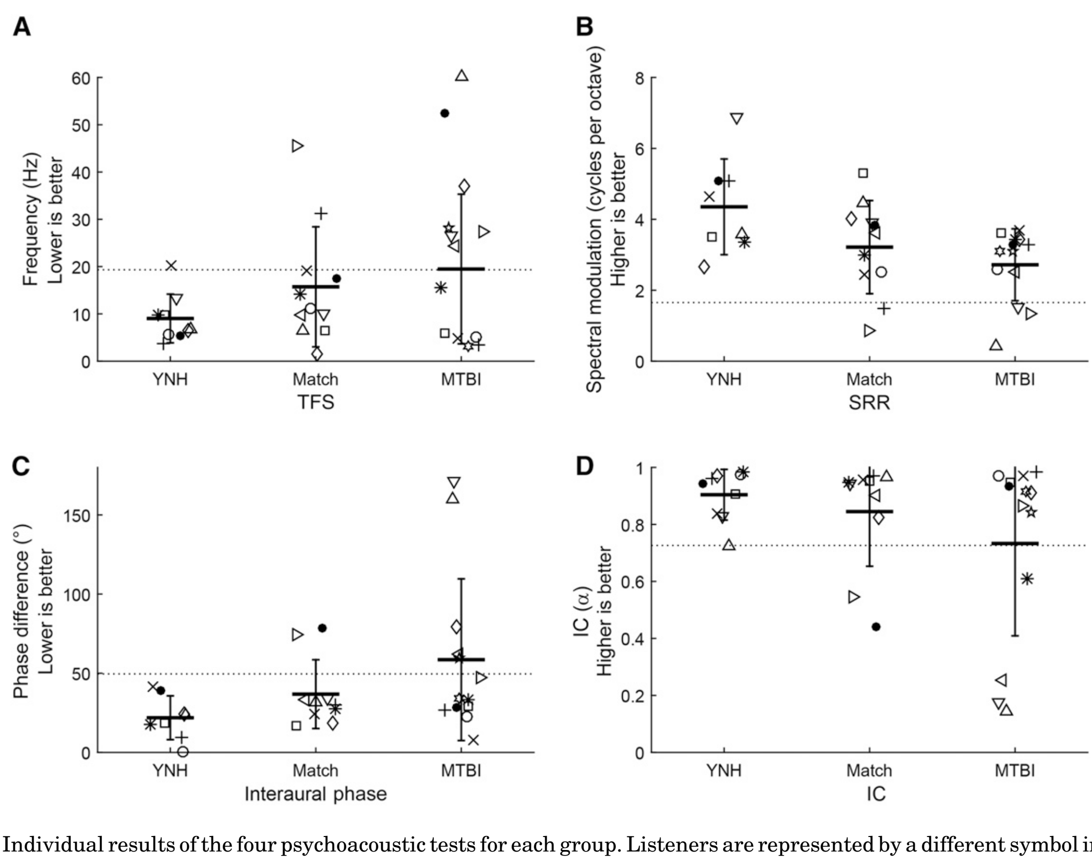

Figure 4. Individual results of the four psychoacoustic tests for each group. Listeners are represented by a different symbol in each group and the symbols correspond to those used in Table 1. Group mean and SD are shown with horizontal bars. Horizontal dashed line represents normal limits as defined by 2 SD worse than YNH mean thresholds.

in the MTBI group had SRR thresholds outside of the normal range of 2 SD above the YNH mean.

Thresholds for IPD were reported in terms of the interaural difference in phase in degrees. Mean and SD thresholds for the YNH group were 21.89 (SD = 13.84) degrees. The YNH thresholds we observed were slightly elevated relative to previously reported thresholds for young listeners with normal pure-tone thresholds obtained using comparable methods (Strelcyk and Dau, 2009; Hopkins and Moore, 2011). This may have been due to differences in the amount of training listeners received, or to differences in the duration and presentation of stimuli. A single listener in the YNH group was unable to perform the task after multiple attempts and reinstruction, leaving a remaining eight listeners in the YNH group. Three listeners (3/11) in the Matched group and five listeners (5/13) in the MTBI group were outside of the normal range established by the mean and SD of the YNH group. Figure 4C shows individual as well as group mean and SD thresholds on the IPD task.

IC thresholds are reported in terms of the α parameter in the stimulus generation algorithm (Hartmann and Cho, 2011), which can range from zero (no IC) to one (total IC). In this task, a higher α indicates better performance. Mean and SD thresholds for the YNH group were 0.904 (SD = 0.0889). Thresholds for the best performers in the YNH group were consistent with previous studies, but several listeners increased the group variance by performing poorly on the task. Based on the mean and SD of the YNH group, a single listener (1/11) in the Matched group and four listeners (4/13) in the MTBI group was considered impaired. Individual and group mean and SD IC thresholds are shown in Figure 4D.

Cognition

Potential group differences in cognition were evaluated with a repeated measures ANOVA using the within-subjects factors of the cognitive measures. A significant group difference [$F_{(2,29.379)} = 5.163$, $p = 0.012$, $\eta_p^2 = 0.269$] was found, as well as a significant effect of cognitive measure [$F_{(1.572,21.869)} = 284.593$, $p < 0.0001$, $\eta_p^2 = 0.910$], but no interaction between group and measure. Greenhouse–Geisser correction of the degrees of freedom and mean squared error was used, due to violation of the sphericity assumption. A Shapiro–Wilk test of normality found no significant violation of the normality assumption; therefore post hoc tests were performed with Bonferroni correction to evaluate group differences across the cognitive measures. No significant group differences were found on any of the three cognitive measures between the MTBI and Matched groups. This result is consistent with the low incidence and small effect size affecting group differences in cognition in cases of long-term MTBI (Tellier et al, 2009). Individual effects of cognition on performance were evaluated through correlational analyses, reported below.

Prediction of Speech-in-Noise and Spatial Release Deficits

The primary purpose of this study was to evaluate the relative contribution of auditory dysfunction to difficulty understanding speech in noise and in competing speech for listeners with a history of MTBI, and to also evaluate the potential contribution of other, nonauditory cognitive factors. To address this question, peripheral auditory, central auditory, and cognitive measures were evaluated in three groups of listeners (an MTBI group, a YNH control group, and a Matched control group consisting of age-matched and pure-tone threshold-matched controls). Stepwise linear regression models were created for each of the speech tasks using the following predictor variables: age, mean pure-tone thresholds at 500, 1000, and 2000 Hz in both ears (pure-tone average [PTA]), TFS, SRR, IPD, IC, working memory, processing speed, and attention. The stepwise regression identified the predictor variable that accounted for the largest proportion of the variance, then continued to find variables that accounted for residual variance in an iterative process, until the remaining variables could not account for a significant portion of the residual variance.

The regression analysis for QuickSIN scores found two factors accounting for 50.4% of the variance ($p < 0.0001$): PTA, which accounted for 39.2% of the variance, and SRR, which accounted for an additional 11.2% of the variance. As SRR is a measure of spectral resolution in the auditory system, it is thought to represent peripheral auditory function, as is the case for PTA. Regression analysis for WIN scores revealed a model that included two factors accounting for a total of 79.5% of the variance. The first factor included in the model was PTA, accounting for 58.9% of the variance in WIN scores, and the second factor was IPD, which accounted for an additional 20.6% of the variance. IPD relies on interaural comparison of phase, which requires phase-locking in the cochlea to be maintained until a binaural comparison is made in the lower auditory brainstem. IPD sensitivity can thus be considered a measure of both TFS and of binaural processing.

The regression model for SRM, computed from the difference in collocated and spatially separated scores to represent the benefit of a spatial separation of talkers, included two factors accounting for a total of 68.8% of the variance. The first factor included in the model, accounting for 53.6% of the variance, was working memory, and the second factor was PTA, accounting for an additional 15.2% of the variance. None of the auditory processing variables entered into the model provided a significant improvement in the variance explained. This result suggests that the SRM task was more sensitive to different listener characteristics than the monaural speech-in-noise tasks, and that cognition, specifically working memory, was the determining factor in listener performance. The fact that the effect of working memory was observed for the difference between collocated and spatially separated conditions was somewhat surprising, given that the difference score was used to remove any shared factors in the collocated and spatially separated conditions. This suggests that those who benefit most from spatial separation are those who have the greatest working memory capacity to make use of the spatial difference.

DISCUSSION

MTBI affects millions of people every year, and there is increasing evidence that a majority suffer persistent neurosensory symptoms (Hoffer et al, 2013). Common postconcussive symptoms include auditory complaints, which may be present and untreated in a majority of cases (Oleksiak et al, 2012), but data remain scarce for civilian populations who lack the auditory comorbidities associated with military service. The impairments that have been found in people with auditory complaints after blast and nonblast injuries include auditory processing deficits that may be associated with elevated pure-tone thresholds (Lew et al, 2007; Gallun et al, 2012; Oleksiak et al, 2012; Saunders et al, 2015).

In the present study, many more listeners in the MTBI group reported difficulty understanding speech in noise than their age-matched and pure-tone threshold-matched peers. Group differences in objective monaural and binaural speech tasks were not significant. Because not all listeners in the MTBI group had auditory complaints, and because the rate of long-term auditory symptoms after MTBI is likely between 16% (Cockrell and Gregory, 1992) and 87.5% (Oleksiak et al, 2012), there was no reason to expect that all of our MTBI participants would demonstrate auditory dysfunction. However, when listeners in the MTBI and Matched groups were recategorized by their stated difficulty in noise, significant objective speech-in-noise and SRM differences were found.

An alternative way to view the effects of MTBI on auditory function is to observe patterns of abnormal auditory test results among listeners and compare the rate of abnormal results across groups (Gallun et al, 2012). The number of abnormal results for each listener was sorted into bins in Figure 5. The chart includes the three speech tests (where a score outside the normal range in either ear was counted as one abnormal result) and the four psychophysical tasks. The sum of abnormal results was then converted to a proportion to facilitate comparison across groups. In the MTBI group, 7/13 (62%) had two or more abnormal results on the speech-in-noise tasks and one or more abnormal result in the psychophysical tasks. Contrast this with the young group, in which only one listener (11%) had abnormal results on more than two tests; and with the matched group, in which four listeners (36%) had more than two abnormal results. Moreover, abnormal results in the matched group were primarily due to the single listener with mild-to-moderate sensorineural hearing loss (the most loss of that group) who had abnormal results on eight of the tests. This listener was recruited to match a single participant in the MTBI group with similar age and audiometric profile. Although limited conclusions can be made from this type of analysis, the pattern of abnormal results across groups is consistent with a higher rate of auditory dysfunction in listeners with a history of MTBI than matched controls. The proportions are also very similar to those reported by Gallun et al (2012; in press), despite the use of different tests and a patient group with and without MTBI diagnoses who had all reported exposure to multiple high-intensity explosions during their military service. It should be noted that in both of those studies, the proportions were also similar to each other, despite the fact that Gallun et al (2012) tested patients within six months of blast exposure and Gallun et al (in press) tested a different group of patients exposed between four and ten years earlier, comparable to the present study.

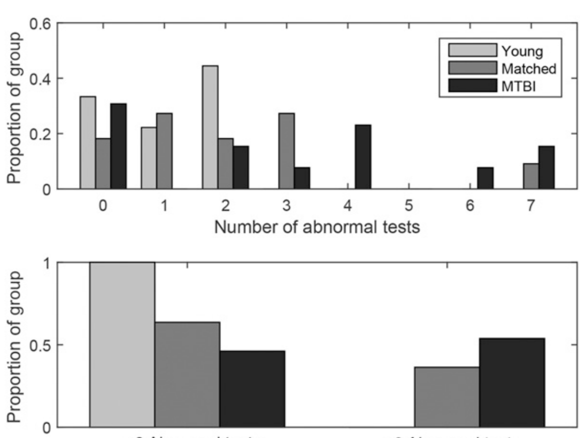

Figure 5. The proportion of listeners who performed in the abnormal range for a given number of tests. Abnormal was defined by clinical normative data for the QuickSIN and WIN tests, and 2 SD worse than the YNH mean for all other tests. The top panel shows the proportion of listeners in integer bins, and the lower panel shows the proportion who had abnormal results on two or fewer tests versus more than two tests. Groups are separated by lightness, with the young group represented by the light grey bars, the matched group in medium grey bars, and the MTBI group in dark grey bars. Note that none of the listeners in the YNH group were abnormal on greater than two tests.

Predictors of Speech Deficits

Results of the regression analysis suggest that different underlying factors contribute to monaural and binaural speech-in-speech and speech-in-noise tasks. In the monaural tasks, variance was best explained by peripheral auditory factors. Furthermore, the factors that best accounted for the residual variance in both tests were auditory processing tasks that are thought to primarily reflect function at the auditory periphery. Despite the variance in age among study participants, aging and cognitive factors that are known to vary with age were not significant predictors of QuickSIN or WIN performance. The conclusion is that suprathreshold deficits associated with mild and subclinical elevation in pure-tone thresholds are the most important factors that affect monaural speech-in-noise tasks. Because individual pure-tone thresholds before the injury are not known in the present study, it is impossible to determine with certainty that MTBI contributed to cochlear damage in these cases, versus threshold elevation secondary to other factors.

Pure-tone thresholds are known to predict QuickSIN and WIN performance (McArdle et al, 2005), though numerous studies have shown that other factors, including a history of traumatic injury, mediate this relationship (Killion and Niquette 2000; Wilson, 2003). In the present study, mild and subclinical pure-tone threshold elevation likely dominated comparisons; future studies should address this issue by determining the relationship between MTBI and pure-tone threshold elevation in participants with preinjury audiometric data (i.e., military service members), and by evaluating speech in noise after MTBI in listeners that meet strict criteria for normal cochlear function.

The role of cognition in SRM spatial benefit was much greater than the monaural speech tasks. Working memory was the factor that accounted for the greatest amount of variance in the benefit of a spatial separation of talkers. This finding was consistent with the relationship between working memory and performance on similar coordinate-response measure tasks (Gygi and Shafiro, 2012).

Clinical Implications

With regard to the myriad potential effects of MTBI, audiologists can do more than assess sensorineural hearing loss. It is only with a comprehensive assessment of the auditory system, including speech-in-noise and psychophysical measures of auditory perception, that auditory complaints following MTBI can be fully enumerated. Failing to quantify impairment in one part of the auditory system can have serious negative consequences for a patient in that their perceived disability is never validated and, in some cases, results in the loss of financial damages or disability compensation.

In addition to providing auditory assessment, audiology can take a role in rehabilitation by addressing the communication needs of the person with MTBI. Whether the source of a brain-injured individual's communication difficulty lies in their auditory system or in domain-general or psychological functions, audiologists can provide counseling and technology that facilitate participation in activities of daily living and rehabilitation services. Even in the absence of a complete understanding of the effects of MTBI on the auditory system, a patient's activity limitations can be addressed using tools such as aural rehabilitation and hearing assistive devices. Anecdotal and case reports indicate that audiologists are currently fitting people who have hearing complaints after MTBI with low-gain hearing aids even in the absence of elevated pure-tone thresholds (Hoover et al, 2014); however, there is currently no data available on the prevalence of this treatment, nor is the practice supported by published clinical guidelines (Hoover et al, 2015).

Future studies should attempt to revise the set of tests performed on patients with MTBI, because existing CAPD tests do not specifically address the impairments likely to result from MTBI. A better understanding of the effects of MTBI on speech recognition, particularly in noisy environments listeners find difficult, and of the auditory processing and cognitive deficits that underlie these difficulties will help improve assessment and rehabilitation after MTBI. Audiology should reassess its role in MTBI care, and can facilitate treatment by addressing the short-term and long-term communication needs of people with postconcussive auditory dysfunction. Rehabilitation after MTBI, including rehabilitation of nonauditory symptoms that rely on auditory communication for assessment and service delivery, may be improved with appropriate diagnosis and treatment of auditory complaints.

REFERENCES

American Psychiatric Association. (2013) *Diagnostic and Statistical Manual of Mental Disorders*. 5th ed. Washington, DC: American Psychiatric Publishing.

Bergemalm PO, Borg E. (2001) Long-term objective and subjective audiologic consequences of closed head injury. *Acta Otolaryngol* 121(6):724–734.

Bergemalm PO, Lyxell B. (2005) Appearances are deceptive? Long-term cognitive and central auditory sequelae from closed head injury. *Int J Audiol* 44(1):39–49.

Bernstein LR, Trahiotis C. (1982) Detection of interaural delay in high-frequency noise. *J Acoust Soc Am* 71(1):147–152.

Bolia RS, Nelson WT, Ericson MA, Simpson BD. (2000) A speech corpus for multitalker communications research. *J Acoust Soc Am* 107(2):1065–1066.

Centers for Disease Control and Prevention (CDC). (2006) Incidence rates of hospitalization related to traumatic brain injury–12 states, 2002. *MMWR Morb Mortal Wkly Rep* 55(8): 201–204.

Cockrell JL, Gregory SA. (1992) Audiological deficits in brain-injured children and adolescents. *Brain Inj* 6(3):261–266.

Cox RM, Alexander GC, Taylor IM, Gray GA. (1997) The contour test of loudness perception. *Ear Hear* 18(5):388–400.

Dean PJ, Sterr A. (2013) Long-term effects of mild traumatic brain injury on cognitive performance. *Front Hum Neurosci* 7:30.

Finkelstein EA, Corso PS, Miller TR. (2006) *The Incidence and Economic Burden of Injuries in the United States*. Oxford, UK: Oxford University Press doi:10.1093/acprof:oso/9780195179484.001.0001.

Flood GM, Dumas HM, Haley, SM. (2005) Central auditory processing and social functioning following brain injury in children. *Brain Inj* 19(12):1019–1026.

Frisina RD. (2001) Subcortical neural coding mechanisms for auditory temporal processing. *Hear Res* 158(1):1–27.

Gallun FJ, Diedesch AC, Kampel SD, Jakien KM. (2013) Independent impacts of age and hearing loss on spatial release in a complex auditory environment. *Front Neurosci* 7:252.

Gallun FJ, Diedesch AC, Kubli LR, Walden TC, Folmer RL, Lewis MS, McDermott DJ, Fausti SA, Leek MR. (2012) Performance on tests of central auditory processing by individuals exposed to high-intensity blasts. *J Rehabil Res Dev* 49(7): 1005–1025.

Gallun FJ, Lewis MS, Folmer RL, Hutter M, Papesh MA, Belding H, Leek MR. (in press) Chronic effects of exposure to high-intensity blasts: Results of tests of central auditory processing. *J Rehabil Res Dev*.

Gygi B, Shafiro V. (2012) Spatial and temporal factors in a multitalker dual listening task. *Acta Acust United Acust* 98(1):142–157.

Hall RC, Hall RC, Chapman MJ. (2005) Definition, diagnosis, and forensic implications of postconcussional syndrome. *Psychosomatics* 46(3):195–202.

Hartmann WM, Cho YJ. (2011) Generating partially correlated noise: a comparison of methods. *J Acoust Soc Am* 130(1):292–301.

Hoffer ME, Balaban C, Nicholas R, Marcus D, Murphy S, Gottshall K. (2013) Neurosensory sequelae of mild traumatic brain injury. *Psychiatr Ann* 43(7):318–323.

Hoofien D, Gilboa A, Vakil E, Donovick PJ. (2001) Traumatic brain injury (TBI) 10-20 years later: a comprehensive outcome study of psychiatric symptomatology, cognitive abilities and psychosocial functioning. *Brain Inj* 15(3):189–209.

Hoover EC, Souza PE, Gallun FJ. (2014) Degraded temporal processing after traumatic brain injury. *J Acoust Soc Am* 135(4): 2166–2166.

Hoover EC, Souza PE, Gallun FJ. (2015) Competing Views on Abnormal Auditory Results After Mild Traumatic Brain Injury. *SIG 6 Perspect Hear Hear Dis Res Diagn* 19(1):12–21.

Hopkins K, Moore BC. (2010) Development of a fast method for measuring sensitivity to temporal fine structure information at low frequencies. *Int J Audiol* 49(12):940–946.

Hopkins K, Moore BC. (2011) The effects of age and cochlear hearing loss on temporal fine structure sensitivity, frequency selectivity, and speech reception in noise. *J Acoust Soc Am* 130(1):334–349.

Humes LE, Dubno JR. (2010) Factors affecting speech understanding in older adults. In: Gordon-Salant S, Frisina RD, Popper AN, Fay RR, Eds. *The Aging Auditory System*, 211–257. New York, NY: Springer.

Jury MA, Flynn MC. (2001) Auditory and vestibular sequelae to traumatic brain injury: a pilot study. *New Zealand Med J* 114(1134):286–288.

Killion MC, Niquette PA. (2000) What can the pure-tone audiogram tell us about a patient's SNR loss? *Hear J* 53(3):46–48.

Krause MO, Kennedy MR, Nelson PB. (2014) Masking release, processing speed and listening effort in adults with traumatic brain injury. *Brain Inj* 28(11):1473–1484.

Levitt H. (1971) Transformed up-down methods in psychoacoustics. *J Acoust Soc Am* 49(2, Suppl):467.

Lew HL, Jerger JF, Guillory SB, Henry JA. (2007) Auditory dysfunction in traumatic brain injury. *J Rehabil Res Dev* 44(7): 921–928.

Mangels JA, Craik FI, Levine B, Schwartz ML, Stuss DT. (2002) Effects of divided attention on episodic memory in chronic traumatic brain injury: a function of severity and strategy. *Neuropsychologia* 40(13):2369–2385.

McArdle RA, Wilson RH. (2006) Homogeneity of the 18 QuickSIN lists. *J Am Acad Audiol* 17(3):157–167.

McArdle RA, Wilson RH, Burks CA. (2005) Speech recognition in multitalker babble using digits, words, and sentences. *J Am Acad Audiol* 16(9):726–739, quiz 763–764.

Moore BC, Glasberg BR, Flanagan HJ, Adams J. (2006) Frequency discrimination of complex tones; assessing the role of component resolvability and temporal fine structure. *J Acoust Soc Am* 119(1): 480–490.

Moore BC, Sek A. (2009) Development of a fast method for determining sensitivity to temporal fine structure. *Int J Audiol* 48(4): 161–171.

Musiek FE, Baran JA, Shinn J. (2004) Assessment and remediation of an auditory processing disorder associated with head trauma. *J Am Acad Audiol* 15(2):117–132.

Noble W, Jensen NS, Naylor G, Bhullar N, Akeroyd MA. (2013) A short form of the Speech, Spatial and Qualities of Hearing scale suitable for clinical use: The SSQ12. *Int J Audiol* 52(6):409–412.

Nölle C, Todt I, Seidl RO, Ernst A. (2004) Pathophysiological changes of the central auditory pathway after blunt trauma of the head. *J Neurotrauma* 21(3):251–258.

O'Jile JR, Ryan LM, Betz B, Parks-Levy J, Hilsabeck RC, Rhudy JL, Gouvier WD. (2006) Information processing following mild head injury. *Arch Clin Neuropsychol* 21(4):293–296.

Oleksiak M, Smith BM, St Andre JR, Caughlan CM, Steiner M. (2012) Audiological issues and hearing loss among Veterans with mild traumatic brain injury. *J Rehabil Res Dev* 49(7):995–1004.

Oxenham AJ, Micheyl C, Keebler MV. (2009) Can temporal fine structure represent the fundamental frequency of unresolved harmonics? *J Acoust Soc Am* 125(4):2189–2199.

Puckette M. (1996) Pure Data: another integrated computer music environment. *Proceedings, Second Intercollege Computer Music Concerts*, 37–41. Tachikawa, Japan: Kunitachi College of Music.

Reitan RM. (1958) Validity of the Trail Making Test as an indicator of organic brain damage. *Percept Mot Skills* 8(3):271–276.

Roup CM, Wiley TL, Safady SH, Stoppenbach DT. (1998) Tympanometric screening norms for adults. *Am J Audiol* 7(2):55–60.

Salthouse TA. (2000) Aging and measures of processing speed. *Biol Psychol* 54(1–3):35–54.

Saunders GH, Frederick MT, Arnold M, Silverman S, Chisolm TH, Myers P. (2015) Auditory difficulties in blast-exposed Veterans with clinically normal hearing. *J Rehabil Res Dev* 52(3):343–360.

Shah P, Miyake A. (1996) The separability of working memory resources for spatial thinking and language processing: an individual differences approach. *J Exp Psychol Gen* 125(1): 4–27.

Souza PE, Blackburn MC, Hoover EC, Gallun FJ. (2014) *Characterizing Severe Hearing Loss*. Scottsdale, AZ: American Auditory Society.

Strelcyk O, Dau T. (2009) Relations between frequency selectivity, temporal fine-structure processing, and speech reception in impaired hearing. *J Acoust Soc Am* 125(5):3328–3345.

Tellier A, Marshall SC, Wilson KG, Smith A, Perugini M, Stiell IG. (2009) The heterogeneity of mild traumatic brain injury: where do we stand? *Brain Inj* 23(11):879–887.

Turgeon C, Champoux F, Lepore F, Leclerc S, Ellemberg D. (2011) Auditory processing after sport-related concussions. *Ear Hear* 32(5): 667–670.

Vanderploeg RD, Curtiss G, Belanger HG. (2005) Long-term neuropsychological outcomes following mild traumatic brain injury. *J Int Neuropsychol Soc* 11(3):228–236.

Wang X. (2007) Neural coding strategies in auditory cortex. *Hear Res* 229(1):81–93.

Wechsler D. (1945) A standardized memory scale for clinical use. *J Psychol* 19(1):87–95.

Whitmer WM, Seeber BU, Akeroyd MA. (2012) Apparent auditory source width insensitivity in older hearing-impaired individuals. *J Acoust Soc Am* 132(1):369–379.

Wilson RH. (2003) Development of a speech-in-multitalker-babble paradigm to assess word-recognition performance. *J Am Acad Audiol* 14(9):453–470.

Wilson RH, Burks CA. (2005) Use of 35 words for evaluation of hearing loss in signal-to-babble ratio: a clinic protocol. *J Rehabil Res Dev* 42(6):839–852.

Won JH, Drennan WR, Rubinstein JT. (2007) Spectral-ripple resolution correlates with speech reception in noise in cochlear implant users. *J Assoc Res Otolaryngol* 8(3):384–392.