Associations Between Auditory Working Memory, Self-Perceived Listening Effort, and Hearing Difficulty in Adults With Mild Traumatic Brain Injury

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Objectives: Mild traumatic brain injury (TBI) can have persistent effects in the auditory domain (e.g., difficulty listening in noise), despite individuals having normal pure-tone auditory sensitivity. Individuals with a history of mild TBI often perceive hearing difficulty and greater listening effort in complex listening situations. The purpose of the present study was to examine self-perceived hearing difficulty, listening effort, and performance on an auditory processing test battery in adults with a history of mild TBI compared with a control group.

Design: Twenty adults ages 20 to 53 years old participated divided into a mild TBI (n = 10) and control group (n = 10). Perceived hearing difficulties were measured using the Adult Auditory Processing Scale and the Hearing Handicap Inventory for Adults. Listening effort was measured using the National Aeronautics and Space Administration-Task Load Index. Listening effort ratings were obtained at baseline, after each auditory processing test, and at the completion of the test battery. The auditory processing test battery included (1) dichotic word recognition, (2) the 500-Hz masking level difference, (3) the Listening in Spatialized Noise-Sentences test, and (4) the Word Auditory Recognition and Recall Measure (WARRM).

Results: Results indicated that individuals with a history of mild TBI perceived significantly greater degrees of hearing difficulty and listening effort than the control group. There were no significant group differences on two of the auditory processing tasks (dichotic word recognition or Listening in Spatialized Noise-Sentences). The mild TBI group exhibited significantly poorer performance on the 500-Hz MLD and the WARRM, a measure of auditory working memory, than the control group. Greater degrees of self-perceived hearing difficulty were significantly associated with greater listening effort and poorer auditory working memory. Greater listening effort was also significantly associated with poorer auditory working memory.

Conclusions: Results demonstrate that adults with a history of mild TBI may experience subjective hearing difficulty and listening effort when listening in challenging acoustic environments. Poorer auditory working memory on the WARRM task was observed for the adults with mild TBI and was associated with greater hearing difficulty and listening effort. Taken together, the present study suggests that conventional clinical audiometric battery alone may not provide enough information about auditory processing deficits in individuals with a history of mild TBI. The results support the use of a multifaceted battery of auditory processing tasks and subjective measures when evaluating individuals with a history of mild TBI.

Key words: Auditory processing, Hearing difficulty, Listening effort, Mild traumatic brain injury, Working memory.

Abbreviations: β = fixed effect coefficient; AAPS = Adult Auditory Processing Scale; DWR = dichotic word recognition; HHIA = Hearing Handicap Inventory for Adults; LiSN-S = Listening in Spatialized Noise-Sentences; MLD = masking level difference; NASA-TLX = National Aeronautics and Space Administration-Task Load Index; p = p value; RM-ANOVAs = repeated measure analysis of variances; SNR = signal to noise ratios; SRT = speech recognition threshold; TBI = traumatic brain injury; WARRM = Word Auditory Recognition and Recall Measure; Z = Z-value.

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INTRODUCTION

Traumatic brain injury (TBI) is most-commonly caused by a sudden impact or acceleration of the head and may result from falls, car accidents, sports injuries, attempts to self-harm, and assaults (Andriessen et al. 2011; Vos et al. 2012; Taylor et al. 2017; Centers for Disease Control and Prevention [CDC] 2019, 2021; Daugherty et al. 2019). There is a relatively high incidence of TBI in the US population. For example, data published by the Center for Disease Control and Prevention indicated that there were approximately 2.8 million emergency department visits, hospitalizations, and deaths related to TBI (Centers for Disease Control and Prevention [CDC] 2019). Mild degrees of TBI account for approximately 75% of TBI cases. In mild cases of TBI, underdiagnosis may be more prevalent than other classifications because there is no clear or measurable site of lesion. Despite the absence of a clear site of lesion, physiologic damage caused by neuronal stretching and axonal injury can create metabolic inefficiencies and result in long-lasting, persistent symptoms (Mckee & Daneshvar 2015). A history of TBI may increase the likelihood of experiencing ongoing auditory and cognitive symptoms that negatively impact quality of life including, but not limited to, memory loss, psychological problems, sensory impairments (e.g., hearing difficulties or vision difficulties), headaches, dizziness, irritability, anxiety, fatigue, and concentration difficulties (Binder 1986; Hurley & Taber 2002).

The mild TBI population is less likely to have persistent symptoms than more severe cases of TBI; however, there is evidence to suggest auditory symptoms may persist for over a decade following injury (Bergemalm & Lyxell 2005; Vander Werff 2012; Hoover et al. 2017; Vander Werff & Rieger 2019; Knoll et al. 2020). In structured environments (e.g., conventional hearing evaluation), individuals with a history of mild TBI typically present with normal auditory and cognitive behaviors. However, when effortful listening is required and/or the cognitive load of the task increases (e.g., listening in a noisy environment), deficits in auditory and cognitive functioning may begin to emerge (Vander Werff 2012; Vander Werff & Rieger 2019). Beyond the periphery, damage to the auditory nervous system due to TBI may result in signal degradation and deficits in efficient and effective processing of auditory stimuli (Oleksiak et al. 2012). Indeed, following mild TBI, some

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individuals report problems processing auditory information or hearing difficulties—particularly in complex listening environments, not explained by their pure-tone sensitivity. The prevalence of subjective hearing difficulties has been reported to be as high as 58% in adults with a history of TBI (Bergemalm & Lyxell 2005). Subjective hearing difficulties following TBI may include difficulty hearing in background noise, difficulty hearing in groups, difficulty understanding rapid speech, challenges remembering spoken information or instructions, and auditory fatigue (Douglas et al. 2000; Bergemalm & Borg 2001; Bergemalm & Lyxell 2005).

Cognition-specific deficits may emerge following TBI, especially when completing mentally demanding tasks. Specifically, following mild TBI individuals may exhibit deficits in working memory (Kumar et al. 2013). Working memory is a cognitive process that provides short-term storage of information for manipulation and maintenance (Baddeley 1992). Information stored in working memory is not typically encoded in either short-term or long-term memory, rather it is collected, then manipulated and used. An example of auditory working memory is the ability to retain a list of the restaurant specials listed by the waiter while concurrently deciding which menu item you would like and then relaying your specific order to the waiter. Working memory, like many cognitive functions, is finite in its capacity and varies between individuals (Baddeley 2006). Further, the ability to successfully take advantage of working memory can also be task dependent (Smith & Pichora-Fuller 2015). For example, a person with a larger, as opposed to a smaller, working memory capacity will have greater ability to allocate cognitive resources to remembering and comprehending when presented with information.

Auditory working memory, also referred to as verbal working memory, is described as the cognitive function used to create the biologic representation of sound for the listener (e.g., environmental, music, and speech sounds; Kraus et al. 2012). Auditory working memory is often measured using a listening span test (originally, Daneman & Carpenter 1980; Waters & Caplan 1996). A typical listening span paradigm involves listening to a set of sentences during which the listener is asked to remember the final word of the sentence, then the listener is asked to recall all of the final words in the set. More recently, Smith et al. (2016) developed the Word Auditory Recognition and Recall Measure (WARRM), which incorporates a listening span measure with a standard word recognition test to create a clinically feasible measure of auditory working memory. Smith et al. validated the WARRM with young normal-hearing adults, older normal-hearing adults, and older hearing-impaired adults. Results of the validation indicated that WARRM scores are highly correlated with the reading span test and speech-in-noise performance, suggesting that the WAARM effectively measures auditory working memory capacity.

Evidence suggests auditory working memory scores correlate with the ability of normal and hearing-impaired listeners to process complex speech signals (Lunner 2003; Rudner et al. 2011; Ward et al. 2016). When an auditory signal is degraded by internal (e.g., suprathreshold deficits) or external (e.g., background noise) factors, the signal is not easily processed and understood by the listener; therefore, the information must be maintained in working memory longer to allow other cognitive processes time to function (Peelle 2018). Following TBI, individuals have a reduced ability to access and use their working memory due to diffuse neural connections being disrupted or altered (Perlstein et al. 2004; Kasahara et al. 2011; Manktelow et al. 2017). For the purposes of the present study, auditory working memory for speech was of particular interest. Measuring auditory working memory for speech provides a specific measure of the ability to temporarily store, use, and comprehend auditory information that is vital to successful communication.

Auditory working memory may also be associated with listening effort in the mild TBI population. When more cognitive effort is allocated to listening, there is less capacity to allocate to working memory (Pichora-Fuller 2016). Listening effort can be defined as the purposeful allocation of cognitive resources when engaging in a listening task (Pichora-Fuller 2016). Another definition describes listening effort as the mental exertion required to attend to and understand an auditory message (McGarrigle et al. 2014). Listening effort has been measured using self-report (Gatehouse & Noble 2004), performance-based behavioral measures (Desjardins & Doherty 2013), and physiologic measures (e.g., pupillometry, Wendt et al. 2016). There is an abundance of literature that reports hearing loss as a significant contributor to increased listening effort due to external (e.g., noise) and internal factors (e.g., age, hearing status, and cognition; McCoy et al. 2005; Baldwin & Ash 2011; Picou et al. 2011; Alhanbali et al. 2018). For example, McLaughlin et al. (2021) found that smaller working memory capacity is related to increased listening effort in older adults. Minimal evidence exists focusing on self-perceived listening effort in individuals with a history of mild TBI. Self-perceived listening effort would be expected to increase following a mild TBI because there are more cognitive resources, like working memory, allocated to listening (Krause et al. 2014). Increased listening effort due to restricted cognitive resources may impact perceived ease of communication, especially in complex listening environments. A study examining masking release and subjective listening effort of individuals with moderate to severe TBI and relatively normal-hearing found that listening effort was significantly greater for individuals with TBI when compared with normal controls (Krause et al. 2014). Though Krause et al. (2014) did not include individuals with mild TBI, it is suspected that individuals with mild TBI may also report greater listening effort when compared with a normative population.

Further, a perceived increase in listening effort could be related to subjective hearing difficulties for individuals with a history of TBI. Subjective hearing difficulty can be defined as the perceived impact of a hearing-related deficits to an individual's daily life. There is evidence to suggest that individuals can perceive more hearing difficulty in the absence of significant shifts in the pure-tone audiogram (Tremblay et al. 2015; Spankovich et al. 2018). Gatehouse and Noble (2004) established associations between self-perceived hearing difficulty and listening effort as measured on the Speech, Spatial, and Qualities of Hearing Scale (originally). It is interesting that, hearing difficulty is a stronger predictor of decreased quality of life than audiometric thresholds (Hallberg et al. 2008; Gopinath et al. 2012; Polku et al. 2018). Therefore, hearing difficulty, in addition to listening effort, is an important consideration for individuals with a history of mild TBI and subjective hearing complaints.

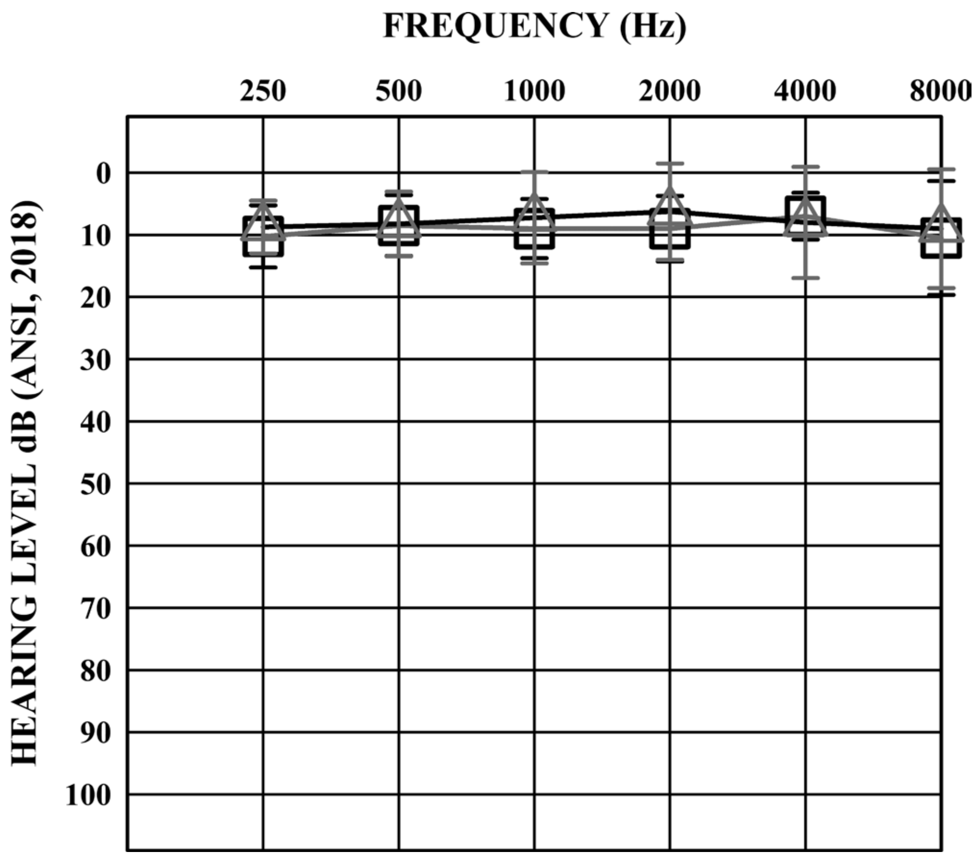

Fig. 1. Mean hearing thresholds (dB HL) and SDs for the right and left ear. The control group represented with black squares (□) and the mild TBI group is represented with gray triangles (△). TBI indicates traumatic brain injury.

Purpose

The purpose of the present study was to quantify the differences in subjective hearing difficulty and listening effort when completing an auditory processing test battery across multiple domains (e.g., speech-in-spatialized noise performance, dichotic listening, binaural integration, and auditory working memory) in adults with near-normal detection abilities, with and without a history of mild TBI. It was hypothesized that the mild TBI group would (1) demonstrate greater subjective hearing difficulties based on questionnaire responses; (2) report greater listening effort before, during, and after the auditory processing test battery; and (3) exhibit poorer performance on auditory processing tasks when compared with the control group.

MATERIALS AND METHODS

The present study was approved by the Behavioral and Social Sciences Institutional Review Board. Participants were recruited from a university student and clinic population and the surrounding areas by using ResearchMatch, a national health volunteer registry that was created by several academic institutions and supported by the U.S. National Institutes of Health as part of the Clinical Translational Science Award program. All participants provided written consent and were compensated for their time. The audiometric equipment used for the study was calibrated in accordance with the appropriate American National Standards Institute standards (American National Standards Institute 1987, 2018).

Participants

Twenty adults between the ages of 18 to 59 years old were recruited. The twenty adults made up two groups, a group of 10 adults with a history of self-reported mild TBI, ages 20 to 58 years old (mean = 38.3 years) and a group of 10 adults, ages 20 to 54 years old (mean = 29.5 years) served as a control group. Mild TBI was described as loss or alteration of consciousness lasting less than 30 min, no or little post-traumatic amnesia, and no known structural damage to the skull or brain. All participants met this criterion as reported in a demographic survey. All participants native language was American English. None of the listeners reported a significant history of middle ear pathologies, noise exposure, or familial history of congenital hearing loss. All participants were right-handed as assessed by The Edinburgh Handedness Inventory (>40 laterality quotient; Oldfield 1971). All participants had normal otoscopic findings and normal middle ear function (Margolis & Heller 1987; Roup et al. 1998; Margolis et al. 2000). Pure-tone thresholds were measured using a Grason-Stadler (GSI) 61 clinical audiometer and ER-3A insert earphones. All participants had pure-tone thresholds ≤25 dB HL for all octave frequencies from 250 to 4000 Hz and no more than 40 dB HL thresholds from 6000 to 8000 Hz. The average audiogram for each group is shown in Figure 1. Air-conduction thresholds were within 10 dB of bone conduction thresholds. The Montreal Cognitive Assessment (Nasreddine et al. 2005) was an indicator of cognitive status for all participants. Montreal Cognitive Assessment scores ranged from 26 to 30 (mean = 29) for the control group and ranged from 25 to 30 (mean = 28.6) for the mild TBI group. Scores were not used as inclusion criteria, however, in accordance with Carson et al (2018), all participant scores fell within the range of no impairment. Additional inclusion criteria for the mild TBI group included a self-reported history of mild TBI in combination with self-reported hearing difficulty as determined by clinical help seeking behavior and informal interview.

Materials and Procedures

Questionnaires • Self-perceived hearing difficulty was measured by the Hearing Handicap Inventory for Adults (HHIA; Newman et al. 1990) and the Adult Auditory Processing Scale (AAPS; Roup et al. 2018, 2021; Woolf & Roup 2019). The HHIA is a 25-item self-assessment of the social and emotional impact of hearing loss and provides insight into the functional impact of an individual's hearing difficulty. The scale includes ratings of "yes," "sometimes," and "no." The AAPS is based on the Children's Auditory Performance Scale (Smoski et al. 1998) and was previously referred to as the Auditory Processing Questionnaire (Roup et al. 2018). This scale is a 36-item questionnaire that assesses self-perceived listening difficulties across six listening conditions. Domains include ideal, quiet, noise, multiple inputs, auditory memory sequencing, and auditory attention span. Each item is rated on a 0 to 6 Likert scale zero indicating "never" and six indicating "always." Responses can be assessed on a domain basis or calculated as a global score. For this study, the global AAPS score was used. Questionnaires were conducted following the determination of inclusion for the study and before the auditory processing test battery. Each participant was given one questionnaire at a time and instructed to read the instructions at the top of each questionnaire. All participants were encouraged to ask the researcher if any part of the questionnaire was unclear. The questionnaire order was counterbalanced across participants.

Measure of Effortful Listening • The National Aeronautics and Space Administration-Task Load Index (NASA-TLX; Hart & Staveland 1988) was used as a measure of listening effort. The NASA-TLX has been utilized as a tool for measuring workload in many different domains, as well as specifically for speech perception tasks (Hart 2006). In cases, where the NASA-TLX is used for speech perception tasks, it is used as a subjective measure of listening effort (Mackersie & Cones 2011; Alhanbali et al. 2019). The NASA-TLX includes six domains, mental, physical, temporal demands, frustration, effort, and performance (Hart & Staveland 1988). In accordance with the preceding categories participants answered the following questions: (1) "How mentally demanding was the task?," (2) "How physically demanding was the task?," (3) "How hurried or rushed was the pace of the task?," (4) "How successful were you in accomplishing what you were asked to do?," (5) "How hard did you have to work to accomplish your level of performance?," and (6) "How insecure, stressed, or annoyed were you?." Each domain was rated on a visual analog scale from 0 to 100. The auditory tasks included in this battery did not require a physical or temporal component, therefore for the purposes of this study, the other four domains were analyzed. The NASA-TLX was administered in both interview style and completed on paper by the participant. Participants were first given the NASA-TLX rating scale via interview style following the completion of a conventional audiometric assessment to act as a baseline measurement, participants were asked to reference the completion of pure-tone audiometry as the auditory task. This was the baseline listening effort for each participant and was compared with a final NASA-TLX rating scale given in interview style following the completion of all auditory processing tasks. Giving the NASA-TLX interview style first also served to familiarize participants with the task. A NASA-TLX rating scale in written form was also completed by each participant following every auditory processing task. Ratings for individual tasks were completed by the participant on paper in the sound booth following each auditory processing task. Scores for the NASA-TLX were calculated based on responses for each domain (mental, effort, frustration, performance) from 0 to 100.

Auditory Processing Tasks • All tasks were chosen to capture the wide range of auditory processing skills. Measures included the domains of competing speech (dichotic word recognition [DWR]), speech-in-noise (Listening in Spatialized Noise [LiSN-S]; Cameron et al. 2011), auditory working memory (WARRM; Smith et al. 2016), and a nonspeech binaural release from masking measure (500 Hz masking level difference [MLD]; Wilson et al. 2003). All auditory processing tasks were conducted in a double-walled sound booth. The order of presentation for the auditory processing tasks was counterbalanced across participants. The 500-Hz MLD, DWR, and WARRM tests were routed from a desktop computer with an external sound card through an audiometer (Grason-Stadler, Model 61) via ER-3A insert earphones and presented at 60 dB HL. The LiSN-S stimuli were presented using Sennheiser supra-aural headphones (HD = 215) routed through headphone socket of the personal computer via a Phonak Buddy universal serial bus sound card.

Dichotic Word Recognition • DWR was measured using 150 consonant vowel consonant words (Boothroyd & Nittrouer 1988; Findlen & Roup 2011, 2016). Each list included 50 words and was phonetically balanced. Consonant vowel consonant words were recorded by a male speaker with the onset cue of "say the word" (Findlen & Roup 2011). For DWR testing, all participants started with free recall, followed by the two directed-recall conditions which were counterbalanced across participants. The free recall condition was always presented first to avoid providing participants with a listening strategy (re: Roup et al. 2006). In the free recall condition, participants were instructed to repeat the words presented in both ears. In the directed-recall conditions, the participants were instructed to repeat the word presented to either the right or left ear only and ignore the word presented to the other ear. DWR was scored in percent correct score out of 50 possible responses for each condition.

500-Hz MLD • The 500-Hz MLD was measured using the paradigm developed by Wilson et al. (2003) and digitized on the Department of Veterans Affairs (2006) compact disc *Speech Recognition and Identification Materials*. The stimuli were a 500-Hz tone and a 500-Hz narrowband noise recorded on two different channels. Stimuli included a signal-in-phase/noise-in-phase (S_0N_0) condition and a signal-out-of-phase/noise-in-phase ($S_\pi N_0$) condition. The signal-out-of-phase condition was a 500 Hz tone that was 180° out of phase between the two ears while the noise was in phase. The test consisted of 33 trials (11 no-tone, 10 S_0N_0, and 12 $S_\pi N_0$) presented at various signal to noise ratios (SNRs). Thresholds were obtained for each condition.

The Spearmen–Kärber method (Finney 1952) was used to determine S_0N_0 and $S_\pi N_0$ thresholds, and the MLD was calculated as the difference between the S_0N_0 and $S_\pi N_0$ conditions.

Word Auditory Recognition and Recall • The WARRM (Smith et al. 2016) concurrently measures word recognition ability and auditory working memory. The WARRM included 100 monosyllabic words in set sizes of 2, 3, 4, 5, and 6 words with five trials of each set size. The stimuli were presented binaurally in quiet. The participant heard the carrier phrase (“you will cite”) followed by the target word. There is a silent interval between the target word offset and the onset of the next carrier phrase during which the participant judges the word by saying “first” or “last.” Indicating if the first letter of the word comes from the first or second half of the alphabet. Cognitive processing is engaged when the participant is instructed to determine (judge) if the first letter of each target word belongs to the first half of the alphabet (A to M) or the second half of the alphabet (N to Z). The WARRM has an equal distribution of letters that begin with the first half versus the second half of the alphabet. After the last target word in each set, there is a 500 msec, 500-Hz tone that serves as a recall prompt followed by a 3000-msec silent interval for the participant to recall as many words as possible from the set. This served as the working memory assessment in the task. Participants were instructed to repeat as many words as they could remember from the set and only to repeat the final word first if that was the only word they could remember. Participants were told not to remember the judgments, just the words. The stimuli were paused in cases where participants needed more time to finish recalling the words in the set. A word recognition, judgment, and recall score can be calculated for each participant. Participant recall responses were counted as correct if the word recalled was the recognized word, even if the recognized word was not the target word for recognition. For example, if the target word was “keep” and the participant recognized the word “knee,” then the recalled word was “knee” this would be a correct response. Participants responses were counted as correct even if the recall order was not the recognition presentation order. The recall score was calculated in percent correct out of 100 possible responses and was used as the measure of working memory performance. The word recognition and judgment scores were not used as experimental variables in this study.

Listening in Spatialized Noise-Sentences • The LiSN-S (Cameron & Dillon 2007a, b; Cameron et al. 2011) used target sentences presented in continuous discourse (two concurrent children’s stories) to determine the listener’s speech recognition threshold (SRT) in four conditions. Target speech was initially presented at 62 dB SPL and the competing discourse remained at a constant level of 55 dB SPL. The target speech was adjusted adaptively for each condition using a computerized bracketing procedure. When a participant correctly identified 50% or more of the words in the target sentence, the SNR was initially increased by 4 dB until participants responded with less than 50% of the sentence. Then the target increased or decreased in 2 dB intervals until the SRT was identified. The LiSN-S is internally calibrated within the software and does not require daily calibration.

Conditions in the LiSN-S use a three-dimensional auditory environment created by synthesizing the speech stimuli with nonindividualized head-related transfer functions. The target talker is always presented at 0°, whereas the distractor discourse varies between 0° and ±90° depending on the condition. Conditions include (1) low-cue, the speaker was the same for both the target and the distractor and the spatial source of the target and the distractor was the same (SV0), (2) vocal separation, the target and the distractor are read by two different talkers, and the spatial source of the sound is the same (DV0), (3) spatial separation, the target and the distractor are separated by ±90°, and speakers are the same (SV90), and (4) high cue, the target and the distractor are separated by ±90° and the speakers are different (DV90). The presentation order of the conditions was consistent with Cameron and Dillon (2007a), DV90°, SV90°, DV0°, and SV0°. Participants were instructed to repeat as much of the sentence as they understood and to guess if they were unsure. Testing ceased when a participant completed 30 sentences in any one condition, or the participant completed the practice sentences plus a minimum of 17 scored sentences and the SE was less than 1 dB. A single SRT was calculated for each condition by calculating the average SNR across completed sentences and the SE was less than 1 dB. If the participant completed all 30 sentences, the SRT was calculated as the average SNR of test sentences. Scores for each LiSN-S condition were used for analysis.

Statistical Analysis

Repeated measure analysis of variances (RM-ANOVAs) was used to analyze DWR, MLD, and LiSN due to the repeated nature of the tasks. Mixed-effects modeling was chosen to assess hearing difficulty, listening effort, and WARRM performance because it examines the items of interest while accounting for variability within and across participants simultaneously. Mixed-effects modeling is considered extremely useful in heterogeneous patient populations such as mild TBI due to its ability to account variability both within and across participants (Harel & McAllister 2019; Brown 2021). For all mixed-effects models, TBI status was treated as a fixed effect and subjects and items were treated as random effects. Mild TBI status was used as a fixed effect because it was expected there would be a common relationship between mild TBI status and responses on tasks included in the study; that is, the effect should operate in a predictable way across different samples. Statistical analyses for the listening effort and the WARRM were conducted using the glmm TMB package (Brooks et al. 2017) in R (R Core Team 2022). Primary statistical analysis for group differences in hearing difficulty was conducted using mixed-effects logistic regression models, using lme4 package (Bates et al. 2015) in R (R Core Team 2022). In these models, significance was evaluated by applying the Satterthwaite approximation of degrees of freedom for *t* tests, and F-tests, implemented using the lmerTest package (Kuznetsova et al. 2017). Spearman’s product moment correlation coefficient was used to assess potential associations between perceived listening effort (NASA-TLX) and subjective ratings of listening ability (HHIA and AAPS). An a priori alpha level was set to 0.05 for all analyses.

RESULTS

Auditory Processing Test Battery

DWR and LiSN Performance • Table 1 provides the means and SDs for all auditory processing tasks in the battery. Minimal differences in performance were observed between the control and mild TBI groups for DWR and LiSN. The DWR data were examined using an RM-ANOVA with group as the between subjects factor, and response condition and ear as the within subjects factors. Results of the RM-ANOVA confirmed that there was not a significant main effect of group for DWR ($F_{1, 18}$ = 0.08, p = 0.78). Results revealed there was a significant main effect of ear, with participants performing significantly better on words presented to the right ear compared with the left ear ($F_{1, 18}$ = 15.10, p = 0.001). There was also a significant main effect of response condition, with participants performing better in the directed recall condition than the free recall condition ($F_{1, 18}$ = 22.03, $p < 0.001$). The LiSN-S data were also examined using an RM-ANOVA with group as the between subjects factor, and response condition as the within subjects factor. Results revealed there was not a significant main effect of group ($F_{1, 18}$ = 0.96, p = 0.34). The within subjects factor of LiSN condition produced a significant main effect ($F_{1, 18}$ = 573.81, $p < 0.001$). Bonferroni corrected pairwise comparisons revealed performance in all conditions (DV90, SV90, DV0, SV0) were significantly different from each other (p = < 0.001). Together, results indicated there are no significant differences in performance on dichotic listening and speech-in-noise auditory processing tasks between the mild TBI and control groups.

500 Hz-MLD Performance • Table 1 provides the means and SDs for 500 Hz-MLD performance of both groups. The TBI group performed worse in the S_0N_0 and $S_\pi N_0$ conditions than the control group, however, the difference in MLD between groups was negligible and nonsignificant (t_{18} = 0.01, p = 0.31). An RM-ANOVA was used to assess performance for the S_0N_0 and $S_\pi N_0$ conditions with groups as the between subjects factor and condition as the within subjects factor. A significant main effect of group was found ($F_{1, 18}$ = 9.40, p = 0.01) confirming that the mild TBI group exhibited poorer S_0N_0 and $S_\pi N_0$ thresholds than the control group. The within subjects factor of condition was also significant ($F_{1, 18}$ = 524.04, $p < 0.001$), with participants performing worse in the S_0N_0 condition. Worse performance in the S_0N_0 condition was expected for both groups compared with the $S_\pi N_0$ condition. Post-hoc t tests revealed a significant group difference between the mild TBI and control group for the S_0N_0 condition (t_{18} = −2.16, p = 0.02) and the $S_\pi N_0$ condition t_{18} = −3.13, p = 0.003. Therefore, adults with a history of mild TBI performed significantly poorer on both 500-Hz MLD conditions than those in the control group.

WARRM Performance • Table 1 reports the descriptive statistics for the WARRM recall score calculated as overall recall score in percent correct. WARRM recall performance was poorer for the mild TBI group (71.60%) when compared with the control group (84.40%). Group differences in word recall on the WARRM were assessed using a mixed-effects model. Subjects and words were treated as random effects, and mild TBI status was treated as a fixed effect. It was assumed randomly sampled subjects and words contribute to the probability of recall in an unknown way. There was a main effect of group (β = −0.88, SE = 0.30, Z_{2000} = −2.99, $p < 0.001$) suggesting participants in the mild TBI group had a higher probability of recalling fewer words on the WARRM than those in the control group. In other words, adults with a history of mild TBI performed significantly worse than those in the control group on the auditory working memory task.

Subjective Hearing Difficulty

Figure 2 presents mean HHIA and AAPS scores for both groups. As seen in Figure 2, the mild TBI group exhibited higher scores than the control group on both questionnaires, indicating greater degrees of hearing handicap (HHIA) and listening difficulty (AAPS). For the HHIA, the mean score for the mild TBI group was 38.80 (SD = 25.50), and the mean score for the control group was 2.00 (SD = 3.80). The mean AAPS global score for the control group was 0.93 (SD = 0.41) and the mean score for the mild TBI group was 2.30 (SD = 0.88). A mixed effects logistic regression model was used to detect group differences in subjective hearing difficulty, with mild TBI status treated as a fixed effect, subjects and questionnaire items were treated as random effects. HIHA results revealed a significant effect of group (β = 1.41, SE =0.24, t = 4.44, $p <$ 0.001). Similarly, the AAPS results revealed a significant effect of group, β = 1.46, SE =0.31, t = 4.48, p = < 0.01. A significant effect of group suggests that individuals with a history of mild TBI perceived significantly higher subjective hearing handicap than the control group on the HHIA and the AAPS.

Subjective Listening Effort

Figures 3A, B present the mean NASA-TLX ratings of both groups at baseline (following audiometric assessment) and following all the auditory processing tasks (final), respectively. The mean baseline listening effort ratings for the mild TBI and control groups were low, ranging from 19 to 47.50 for mental demand, effort, and frustration. Mean ratings for performance were high at 71.50 and 74.50 for the mild TBI and control groups, respectively. It is clear there is little difference in baseline subjective listening effort between the two groups. Table 2 presents the results of a linear mixed model used to assess group differences in listening effort with TBI status treated as a fixed effect and subjects

TABLE 1. M and SDs for 500-Hz MLD conditions, DWR conditions, SRTs by condition for LiSN-S and word recall score for the WARRM

	500 Hz MLD (dB)		DWR (%)				LiSN-S (dB SNR)				
Group	$S_\pi N_0$	S_0N_0	Free Recall Right	Free Recall Left	Directed Recall Right	Directed Recall Left	DV90	SV90	DV0	SV0	WARRM (%)
Control											
M	−27.00	−13.20	90.60	84.80	95.40	92.60	−14.95	−13.91	−10.87	−1.94	84.40
SD	1.67	2.86	2.50	10.29	1.35	3.35	1.52	2.71	1.89	1.37	7.99
mTBI											
M	−23.80	−10.60	91.00	84.00	95.60	90.60	−14.74	−13.01	−10.35	−0.88	71.60
SD	2.74	2.50	7.26	10.11	3.10	5.82	1.71	1.74	2.02	1.13	10.47

DWR, dichotic word recognition; LiSN-S, Listening in Spatialized Noise-Sentences; M, means; MLD, masking level difference; mTBI, mild traumatic brain injury; SRT, speech recognition threshold; WARRM, Word Auditory Recognition and Recall Measure.

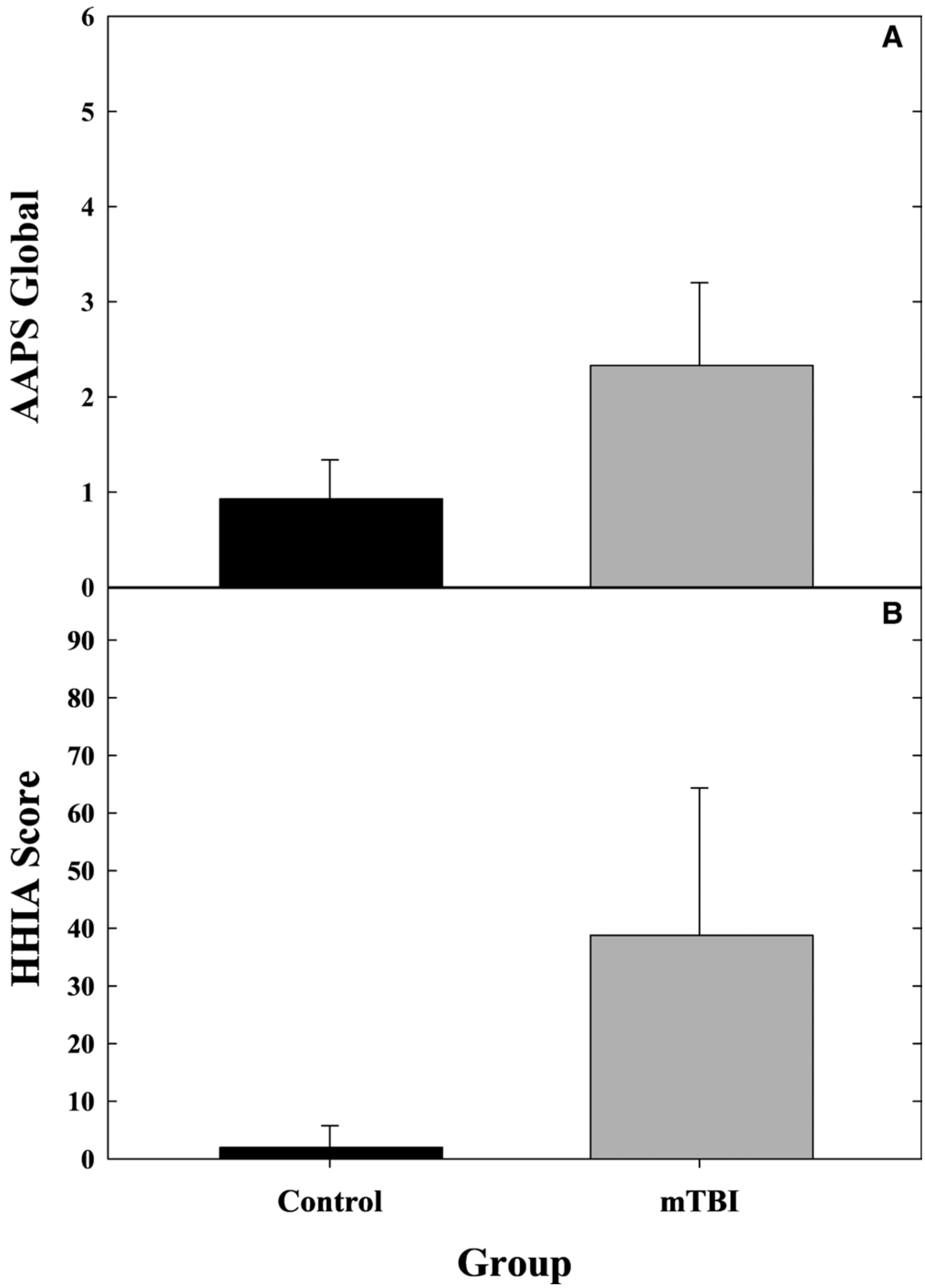

Fig. 2. Average scores with SDs for subjective hearing difficulty on the AAPS and HHIA by group. A, Mean AAPS global score on the abscissa and group on the ordinate. B, Mean HHIA scores on the abscissa and group on the ordinate. The mean scores for the control group are represented in black and the mean score for the mild TBI group is represented in gray. Error bars represent one SD from the mean. AAPS indicates Adult Auditory Processing Scale; HHIA, Hearing Handicap Inventory for Adults; TBI, traumatic brain injury.

and items treated as random effects. Table 2, row 1 presents the baseline results, indicating there were no significant differences between the mild TBI and control groups in any domain on the NASA-TLX at baseline. Figure 3B presents the final assessment of listening effort. The mean listening effort final scores for the mild TBI group were much higher than baseline and ranged from 62.50 to 82.50 for mental demand, effort, and frustration. The mild TBI group rated their mean performance low, with a rating of 47.00. The control group ratings were relatively increased from baseline ranging from 35.50 to 51.00. Mean ratings of performance for the control group were still relatively high at 66.50. Table 2, row 2 compares the final ratings of the mild TBI and control groups, in all four domains the mild TBI group rates their listening effort as significantly different from the control group. Figure 3 visually demonstrates large differences in subjective listening effort as measured by the NASA-TLX between the two groups following the auditory processing tasks. Significant differences between groups suggest the mild TBI group perceived significantly greater effort after completing the auditory processing tasks compared with the control group.

Listening effort was also evaluated at the task level. For mental demand, effort, and frustration, higher scores indicate more difficulty. Overall, the mild TBI group reported greater listening effort on the NASA-TLX. Mean ratings of mental demand ranged from 42.50 to 96.50 for the mild TBI group and 19.00 to 71.00 for the control group. The mild TBI group rated mental demand as significantly more demanding for all tasks (i.e., DWR, MLD, LiSN-S, and WARRM) than the control group. Individual *p* values for the tasks are presented in Table 2. Mean ratings for effort during the tasks ranged from 51.50 to 94.00 for the mild TBI group and 26.00 to 66.00 for the control group. The mild TBI group perceived that they exerted significantly more effort for all tasks than the control group. Mean ratings for frustration ranged from 35.00 to 89.50 for the mild TBI group and 15.00 to 45.00 for the control group. The mild TBI group rated the MLD, LiSN-S, and the WARRM as significantly more frustrating than the control group. There was no significant difference in frustration for the DWR task. Mean ratings of performance ranged from 25.50 to 63.00 for the mild TBI group and 55.00 to 78.00 for the control group. Lower ratings indicate poorer performance. The mild TBI group rated their performance as significantly worse than the control group for the LiSN-S and WARRM. There were no significant perceived differences in performance for DWR and MLD. Together, listening effort as measured by the NASA-TLX revealed the mild TBI group perceived significantly greater mental demand and effort during all of the tasks. The mild TBI also reported significantly greater frustration for three tasks (MLD, LiSN-S, and WARRM) and perceived worse performance on two of the tasks (LiSN and WARRM).

Correlations

The associations between subjective hearing difficulty and subjective listening effort were examined using Spearman's product moment correlational analysis. Figure 4A presents a bivariate plot of the HHIA as it relates to participants final subjective listening effort rating. Results indicate mental demand ($r = 0.71$, $p < 0.001$), effort ($r = 0.64$, $p = 0.002$), and frustration ($r = 0.74$, $p < 0.001$) were all found to have a positive significant strong correlation with HHIA scores. A positive association between the NASA-TLX and the HHIA indicates that individuals who perceive greater subjective listening effort also rate hearing handicap as higher on the HHIA. Figure 4B presents a bivariate plot of the AAPS global score as a function of the final subjective

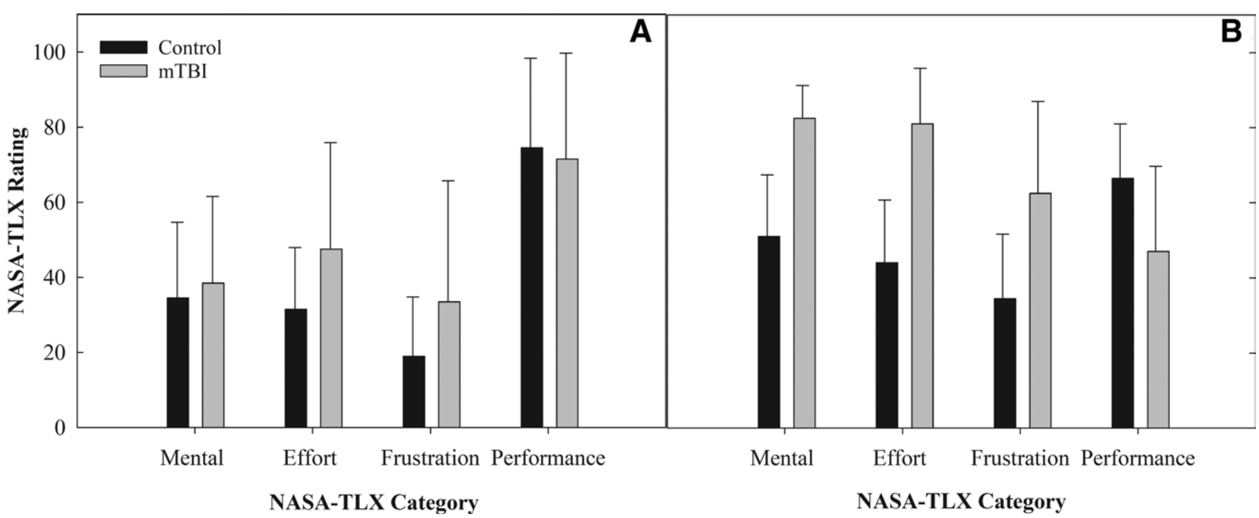

Fig. 3. NASA-TLX ratings are organized by category on the on the abscissa for all three graphs. A and B, The mean NASA-TLX rating on the ordinate. A, Baseline ratings of the NASA-TLX for the control vs. the mild TBI group. B, The final ratings. Error bars for all graphs represent one SD from the mean. NASA-TLX indicates National Aeronautics and Space Administration-Task Load Index; TBI, traumatic brain injury.

TABLE 2. Statistical analysis using a linear mixed model comparing the listening effort of individuals with a history of mild TBI to the control group, as rated on the NASA-TLX at baseline, after each test, and post-test battery (final)

	Mental Demand				Effort				Frustration				Performance			
Comparisons	β	SE	Z	p	β	SE	Z	p	β	SE	Z	p	β	SE	Z	p
Baseline	0.01	0.47	0.03	0.97	0.48	0.34	1.01	0.31	0.46	0.49	0.96	0.34	0.09	0.51	0.18	0.86
Final	1.31	0.38	3.42	<0.001**	1.63	0.39	4.22	<0.001**	1.28	0.37	3.41	<0.001**	−1.06	0.37	−2.86	0.004**
DWR	1.11	0.49	2.26	0.02*	1.55	0.49	3.12	0.002**	0.73	0.50	1.47	0.14	−0.42	0.53	−0.77	0.44
MLD	1.13	0.44	2.60	0.01*	1.04	0.42	2.51	0.01*	1.04	0.45	2.34	0.02*	0.17	0.42	0.40	0.69
LiSN-S	1.31	0.43	3.05	0.002**	0.99	0.42	2.35	0.02*	1.70	0.41	4.15	<0.001**	−0.82	0.40	−2.05	0.04*
WARRM	1.53	0.41	3.70	<0.001**	1.76	0.40	4.38	<0.001**	2.32	0.40	5.76	<0.001**	−1.64	0.38	−4.35	<0.001**

Four domains of the NASA-TLX were used to capture the perceived listening effort of individuals: mental demand, effort, frustration, and performance. The number of observations for each comparison was 1600.
$^*p < 0.05$,
$^{**}p < 0.01$.
β, fixed effect coefficient; NASA-TLX, National Aeronautics and Space Administration-Task Load Index; p, p value; TBI, traumatic brain injury; Z, Z-value.

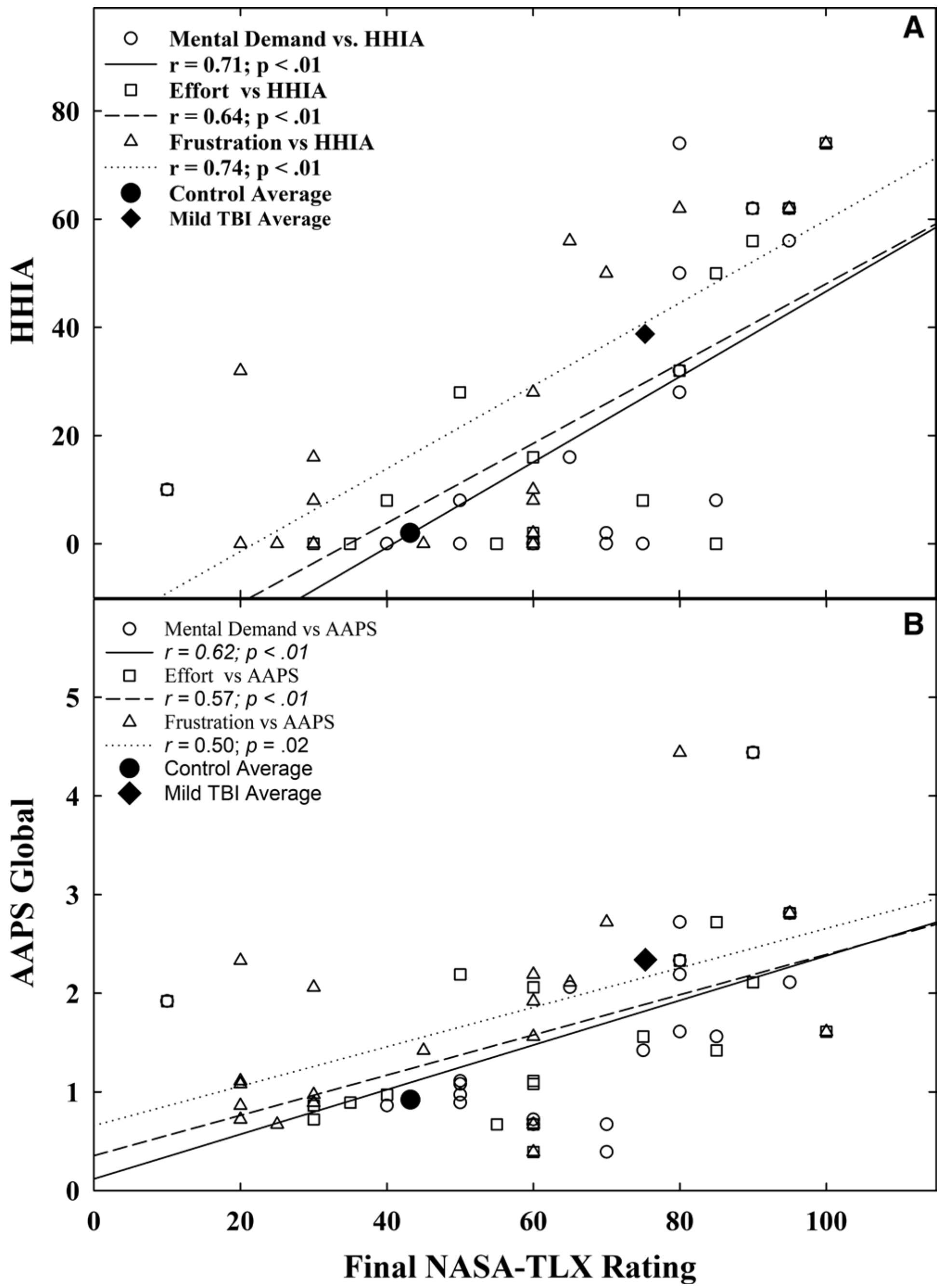

Fig. 4. Correction analysis of subjective hearing difficulty (HHIA & AAPS) and subjective listening effort (NASA-TLX). A, Individual data as a bivariate plot with NASA-TLX postauditory processing tasks (final) on the abscissa and HHIA scores are on the ordinate. B, Individual data presented as bivariate plot with the same abscissa and AAPS global score on the ordinate. Categories of the NASA-TLX are represented by different symbols in the plot: mental demand (○), effort (□), and frustration (△). The lines represent the regression from the mean. The filled circle (●) represents the average for the control group and the filled diamond (◆) represents the average for the mild TBI group. AAPS indicates Adult Auditory Processing Scale; HHIA, Hearing Handicap Inventory for Adults; NASA-TLX, National Aeronautics and Space Administration-Task Load Index; TBI, traumatic brain injury.

listening effort rating. Results indicated that NASA-TLX ratings of mental demand (r = 0.62, p = 0.004), effort (r = 0.57, p = 0.009), and frustration (r = 0.50, p = 0.02) had a positive significant (<0.05) moderate correlation with the global AAPS score. A significant positive correlation between the NASA-TLX and the AAPS indicates that individuals who perceive greater subjective listening effort also report higher global scores on the AAPS. The correlation between subjective hearing difficulty and perception of performance (NASA-TLX) was also measured. Performance is rated as 0-poor performance to 100-perfect performance, thus negative correlations were expected. However, significant correlations between self-perceived hearing ability and performance were not found (p > 0.05).

The correlation between working memory and subjective hearing difficulty was also examined using Spearman's product moment correlation analysis. Results indicated that the WARRM recall score had a significant moderate negative correlation with both the HHIA (r = −0.47, p = 0.04) and the AAPS global scores ($r = -0.50$, $p = 0.03$). A negative association between working memory performance and subjective hearing difficulty indicates that individuals with poorer working memory scores reported greater hearing difficulty. Figure 5 represents the correlations between working memory and subjective listening effort. Results indicated that WARRM recall scores had significant moderate correlations with task specific and final listening effort ratings on the NASA-TLX. The WARRM recall score was moderately related to effort ($r = -0.54$, $p = 0.01$), frustration ($r = -0.47$, $p = 0.04$) and performance ($r = 0.49$, $p = 0.03$) and not related to mental demand ($r = -0.42$, $p = 0.07$) for the task specific NASA-TLX rating. The WARRM recall score was also moderately correlated to final mental demand ($r = -0.48$, $p = 0.03$), final effort ($r = -0.55$, $p = 0.01$), and final frustration ($r = -0.56$, $p = 0.01$), but not related to final performance ($r = 0.70$, $p = 0.76$) on the final NASA-TLX rating. Together, the associations between working memory and subjective listening effort suggest that individuals with poorer working memory report greater degrees of listening effort during the WARRM task and overall.

The associations between the other auditory processing tasks (DWR, MLD, and LiSN) and the hearing difficulty and listening effort were also examined. Results indicated that the AAPS global score had a significant moderate positive correlation with $S_\pi N_0$ condition of the MLD ($r = 0.55$, $p = 0.01$) and SV90 ($r = 0.46$, $p = 0.04$) and SV0 ($r = 0.53$, $p = 0.02$) conditions of the LiSN. Similarly, the HHIA had moderate positive correlation with $S_\pi N_0$ condition of the MLD ($r = 0.61$, $p = 0.004$) and SV90 ($r = 0.52$, $p = 0.02$) and SV0 ($r = 0.49$, $p = 0.05$) conditions of the LiSN-S. Neither measure of hearing difficulty was associated with the DWR task. Overall, hearing difficulty was associated with three of the four behavioral measures.

The association between listening effort ratings for each task and task performance was also assessed. For DWR, only the directed right condition was significantly positively moderately correlated with ratings on the NASA-TLX, for mental demand, effort, and frustration ($r = 0.47$ to 0.51, $p = 0.02$ to 0.04). For the 500-Hz MLD, only the $S_\pi N_0$ condition was significantly moderately correlated with the effort and frustration ratings on the NASA-TLX ($r = 0.61$ to 0.62, $p = 0.004$). Although overall participants did not rate the 500-Hz MLD as a mentally demanding task, poorer performance on the MLD was associated with increased task effort and frustration. For the LiSN-S task, only SV0 performance, the most difficult condition, was significantly moderately correlated with mental demand and frustration ($r = 0.51$ to 0.52, $p = 0.02$) on the NASA-TLX. Indicating that those who performed more poorly perceived greater mental demand and experienced more frustration with the task. LiSN-S DV90, SV90, and DV0 performance were significantly moderately correlated with effort ratings on the NASA-TLX ($r = 0.46$ to 0.59, $p = 0.007$ to 0.04). Increased ratings of effort suggest that individuals who performed more poorly exerted more effort to complete the task.

Individual Analysis

The mild TBI population is known for its variability among participants, therefore it is important to address individual performance to provide a more complete picture of the mild TBI group. Table 3 addresses the number of abnormal tests in the battery for each individual mild TBI subject and provides subject-specific information regarding age, number of mild TBIs, and years since injury. Abnormal scores falling two SDs and one SD below the mean are represented relative to the control group in any condition of the auditory processing task. The final column represents the total number of abnormal test results for each mild TBI subject. In accordance with American Speech-Language-Hearing Association (n.d.) standards, those with two or more auditory processing tests that fall outside of the normal range are considered to have an auditory processing disorder. One SD was used to increase sensitivity due to the mild TBI group having high reports of hearing difficulty. Another way to consider this data is to look at the percentage of individuals who performed abnormally in each task. Overall, 40 to 80% of the mild TBI group performed abnormally on the

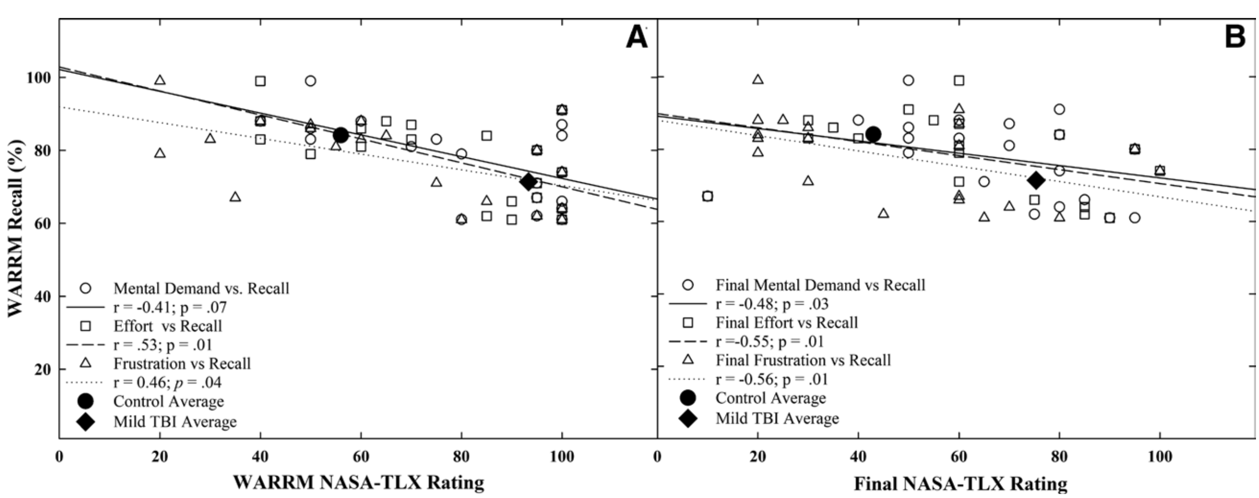

Fig. 5. Correlation analysis of WARRM Recall score by task specific and final NASA-TLX ratings. A, Individual data as a bivariate plot with the task specific WARRM NASA-TLX rating on the abscissa and WARRM performance on the ordinate. B, Individual data presented as bivariate plot of the final NASA-TLX, postauditory processing tasks, on the abscissa and has the same ordinate. Categories of the NASA-TLX are represented by different symbols in the plot: mental demand (○), effort (□), and frustration (△). The lines represent the regression from the mean. The filled circle (●) represents the average for the control group and the filled diamond (◆) represents the average for the mild TBI group. NASA-TLX indicates National Aeronautics and Space Administration-Task Load Index; TBI, traumatic brain injury; WARRM, Word Auditory Recognition and Recall Measure.

TABLE 3. Self-reported demographic information related to the mild TBI and abnormal individual performance for each listening task

	Demographic Information			Listening Tasks				
Subject	Age (yrs)	Number of Mild TBIs	Time Since Last Injury (yrs)	DWR	MLD	LiSN	WARRM	Number of Tasks Containing Abnormal Performance
1	22	1	10					3
2	23	3	3					1
3	20	2	5					0
4	56	3	7					3
5	58	1	2					2
6	52	4	7					2
7	41	2	6					2
8	52	1	8					3
9	26	1	3					3
10	33	3	22					3

Abnormal performance is represented as one SD in light gray and two SDs are represented in dark gray.
DWR, dichotic word recognition; LiSN, Listening in Spatialized Noise; MLD, masking level difference; TBI, traumatic brain injury; WARRM, Word Auditory Recognition and Recall Measure.

auditory processing tasks, falling one to two SDs below the mean of the control group. This is compared with the control group, where only 10 to 20% performed, one to two SD outside of the mean for two or more tasks. Only one participant had a task that fell two SDs outside of the normal range. Further, none of the control participants meet the qualification of auditory processing disorder as defined by American Speech Language and Hearing Association. When breaking the auditory processing results down by task, 50% of the mild TBI group performed abnormally for DWR, 80% for MLD, 30% for LiSN-S, and 70% for WARRM. Table 3 also demonstrates how individual participants with mild TBI performed abnormally on different measures of auditory processing. Differential performance among individuals with mild TBI suggests a single behavioral examination of auditory processing abilities is not appropriate for the mild TBI population.

DISCUSSION

The mild TBI population is unique because approximately 85 to 90% of individuals recover with no lasting, recognizable effects from the injury and can return to their activities of daily living without increased difficulty (Losoi et al. 2016). Nevertheless, there is a growing body of evidence highlighting a subset of adults who experience ongoing and persistent auditory symptoms following mild TBI (Vander Werff 2012; Hoover et al. 2017; Vander Werff & Rieger 2019; Knoll et al. 2020; Roup et al. 2023). Specifically, patients complain of having trouble hearing in background noise, trouble with localization, sensitivity to sound, and listening fatigue (Douglas et al. 2000; Bergemalm & Borg 2001; Bergemalm & Lyxell 2005). It is important to note that, most of the symptoms experienced by this subset of individuals do not rise to the level of impaired auditory function when tested with traditional clinically used audiologic measures. Therefore, in addition to behavioral measures of auditory processing, it was also of interest to examine subjective hearing difficulty and listening effort in individuals with and without a history of mild TBI. Previously, hearing difficulty has been reported in the TBI population (Saunders et al. 2015; Hoover et al. 2017; Knoll et al. 2019, 2020). Following mild TBI individuals are more likely to have social and emotional consequences such as anxiety, depression, and social isolation (Binder 1986; Hurley & Taber 2002), which may be directly or indirectly related to their subjective hearing difficulty.

Individuals who experience greater hearing difficulty are also likely to report greater listening effort, especially when listening in complex auditory environments (Alhanbali et al. 2018). Although comparison of the baseline measures of listening effort revealed no group differences, when examining the final rating of listening effort, significant differences between the mild TBI and control groups were found for every domain (mental demand, effort, frustration, and performance). In addition, when listening effort was examined at the task level, the mild TBI group perceived significantly greater mental demand and effort relative to the control group after all auditory processing tasks. For the LiSN-S and the WARRM, the mild TBI group also reported significantly higher frustration and significantly lower ratings of their performance on the tasks compared with the control group. This suggests that for all auditory processing tasks in the battery, individuals with a history of mild TBI perceived the allocation of more listening effort to complete auditory tasks compared with the control group.

Similar results to the present study were reported by Krause et al. (2014) who demonstrated that individuals with a history of TBI reported higher levels of listening effort during speech-in-noise tasks. The present study differs from Krause et al. by focusing specifically on individuals with mild TBI, rather than classifications of TBI from moderate to severe. Notably, individuals with a history of mild TBI may present with more subtle reports of listening difficulty than those with more severe etiologies. Together, the findings of the present study and Krause et al. suggest deficits following TBI can manifest in the auditory domain and result in notable changes in listening effort for individuals with a history of TBI of any severity (mild to severe).

In addition, significant moderate to strong positive associations between the hearing difficulty (i.e., AAPS global scores and HHIA scores) and participants' final rating of subjective listening effort on the NASA-TLX were observed. The associations between hearing difficulty and listening effort suggest the adults with mild TBI who perceived greater hearing difficulty also perceived greater listening effort during complex listening tasks. An association between greater subjective hearing difficulty and greater listening effort is consistent with other populations (Gatehouse & Noble 2004; Alhanbali et al. 2018). For example, Gatehouse and Noble (2004) and Alhanbali et al. (2018) both conducted studies comparing individuals with hearing loss to a control population and found hearing loss to be strongly correlated with listening effort. To the authors' knowledge, this is the first study examining the correlation of subjective hearing difficulty and listening effort in the mild TBI population. Evidence from the present study showed subjective listening effort is closely tied to self-perception of hearing-related difficulties, suggesting subjective measures of hearing difficulty may help to predict listening effort. Including an already established questionnaire (e.g., HHIA or AAPS) for patients with a history of mild TBI may have important implications to identifying individuals exhibiting greater listening effort. Prolonged listening effort can result in greater listening fatigue which in turn can lead to adverse outcomes for the patient (Pichora-Fuller et al. 2016; Alhanbali et al. 2019) Notably, questionnaires regarding hearing-related difficulties are highly accessible to audiologists and provide a relatively fast additional piece of evidence to match patient reports.

In older adults with hearing loss, the correlation between working memory and performance in complex acoustic environments has been established (Rudner et al. 2011). Generally, deficits in auditory working memory may contribute to complaints related to listening in complex acoustic environments. Deficits in working memory have been identified in some individuals following mild TBI (Saunders et al. 2015; Vander Werff & Rieger 2019) and may help to explain some auditory processing difficulties following mild TBI. Chung et al. (2019) found that following mild TBI, individuals had less neural associations related to working memory when compared with a control group, suggesting a measure of working memory may help identify deficits in the mild TBI population. The present study hypothesized that individuals with mild TBI would perform more poorly on a working memory task than a control group. Results of the WARRM task confirmed that the mild TBI group exhibited significantly poorer auditory working memory ability than the control group. In other words, when presented with auditory stimuli, those with a history of mild TBI and hearing difficulty were less able to store and use verbal stimuli for recall when compared with a control group.

Further, working memory performance was significantly associated with subjective hearing difficulty and listening effort. In a real-world listening scenario, the use of working memory is essential. Working memory allows the individual to continually update necessary conversational information, shift between speakers, and inhibit other distracting auditory information (Miyake et al. 2000; Rudner et al. 2011). However, if an individual's working memory capacity is already met by the demands of recognizing the auditory signal, any additional processing (e.g., storage in working memory for recall), will not be possible. Together, these results suggest that the mild TBI group may have working memory deficits and those deficits lead to challenges in functional communication and the perception of greater hearing difficulty and listening effort.

The 500-Hz MLD is a nonspeech measure of auditory processing during which the individual must assess interaural temporal cues to detect subtle differences in the signal. The present study found the mild TBI group performed significantly poorer in both the $S_{\pi}N_0$ and the S_0N_0 conditions suggesting that the 500-Hz MLD may be sensitive enough to detect changes in the auditory processing abilities of individuals with a history of mild TBI. A study conducted by Grant et al. (2021) found that blast-exposed Veterans demonstrated significantly poorer performance in $S_{\pi}N_0$ and the S_0N_0 conditions despite similar MLD scores. The present study and Grant et al.'s study demonstrate that the release from masking is similar between individuals with and without a history of TBI. However, following a TBI, the ability to detect the target signal is significantly worse than the control groups. Helfer and Jesse (2021) suggest poorer processing of the auditory signal may be contributing to differences in subjective hearing difficulty and listening effort in middle-aged adults. Similarly, deficits in binaural auditory processing following mild TBI may contribute to increased reports of hearing-related complaints.

Group differences between the mild TBI and the control group were not found for the two of the auditory processing tasks (LiSN, or DWR). It is interesting that, poorer task performance in some conditions was correlated with greater subjective hearing difficulty and listening effort, despite no measurable difference in behavioral performance. Literature regarding auditory processing deficits following mild TBI is currently mixed. Hoover et al. (2017) found no differences in a battery of auditory processing tasks between a mild TBI and control group. The present study methodology was similar to the Hoover et al. study because both had small sample sizes and a large age range of participants, likely increasing the variability within groups. In contrast, Vander Werff and Rieger (2019) found group differences between individuals with a history of mild TBI and a control group on a battery of auditory processing tasks. The group of mild TBI participants used in the Vander Werff and Rieger study was larger and was recruited based on help seeking behavior related to persistent auditory symptoms. The presence of persistent auditory complaints may account for some of the variability in performance on auditory processing tasks, suggesting a mild TBI can have auditory, domain-specific consequences. Although this study did recruit individuals with auditory complaints, the sample size may have limited the ability to see group differences in performance on all auditory processing tasks.

As previously noted, individuals with a history of mild TBI are highly variable in their performance on auditory and non-auditory tasks (Oleksiak et al. 2012), such that group-level statistical analysis may mask individual deficits in performance. Although examining results at the group level is essential, highly variable populations like those with mild TBI warrant individual examination. As expected, there were high degrees of variability in performance across auditory processing tasks completed by the mild TBI group in this study, meaning some individuals performed well on one task and others performed poorly on the same task. Despite a lack of significant differences at the group level, when examined at the individual level, 30% of mild TBI participants would be identified to have an auditory processing disorder in accordance with American Speech Language and Hearing Association's standard of two or more auditory processing tasks being abnormal by two or more SDs below the mean (American Speech-Language-Hearing Association n.d.). In comparison, Oleksiak et al. (2012) conducted a review of patients with a history of mild TBI and found 16.2% of individuals had abnormal performance and were classified as having an auditory processing disorder. The difference in prevalence of abnormal findings noted between the present study and Oleksiak et al. is likely due to the present study specifically recruiting individuals with complaints in the auditory domain. Turgeon et al. (2011) studied individuals with a history of concussion and reports of postconcussive symptoms. Turgeon et al. found that 63% of individuals with a history of concussion (i.e., mild TBI) would be classified as having an auditory processing disorder. Again, screening specifically for symptomatic individuals with a history of mild TBI seems to help differentiate individuals more likely to have auditory processing deficits from those who do not have auditory-related consequences.

Further, Table 3 also presents tasks where individuals with mild TBI performed one SD (lighter shading) outside of the mean. One SD below the mean was reported in accordance with other studies on mild TBI (Cicerone 1996) and may capture more subtle auditory processing changes following mild TBI. Although not clinically significant, subtle suprathreshold changes may contribute to a greater perception of subjective hearing difficulty and may help explain reports of hearing difficulty. If one SD from the mean is used, 80% of individuals have two or more abnormal results. All individuals in the 80% group had one test that was two SDs below the mean, which may not be considered clinically significant following American Speech-Language-Hearing Association (n.d.) standards, however provide evidence of the subtle changes that can occur following a mild TBI. Clearly, variability of auditory processing performance is a hallmark of individuals following mild TBI. As a result, clinicians should strongly consider individual subjective reports, task specific performance, and composite scores (re: the SCAN:3-A; Keith 2009) from their battery when evaluating individuals with mild TBI.

CONCLUSIONS AND CLINICAL IMPLICATIONS

Individuals with a history of mild TBI and subjective hearing difficulty may seek out audiologic care, therefore it is critical to be familiar with the clinical presentation of the mild TBI population. The present study suggests that reported hearing difficulty, listening effort, and considerations of cognitive factors, such as working memory, may be a critical piece in the auditory differential diagnosis in the mild TBI injury population. Further, performance on behavioral tests is highly variable in the mild TBI population. Rather than relying solely on conventional or behavioral testing, a dynamic approach to accessing an individual's subjective complaints and a battery of auditory processing tasks will likely result in the best outcomes for individuals with a history of mild TBI. In addition, audiologists may want to consider mild gain amplification as a treatment option for patients with a history of mild TBI considering there is evidence to suggest mild gain amplification is successful for other populations with auditory processing deficits and attentional difficulties (Roup et al. 2018; Singh & Doherty 2020).

The results from this study should be interpreted and used carefully. The study found significant results, but interpretations were limited by a small sample. In addition, the performance on auditory processing tasks was highly variable for mild TBI participants; therefore, results can be considered as a group but should also be examined at the individual level. Further, the present study included individuals with a large range of ages (18 to 58 years), which may have contributed to the variability observed in their auditory processing performance. For example, recent data from our lab found significantly poorer auditory processing performance for a group of middle-aged adults with mild TBI compared with a separate group of young adults with mild TBI (Roup et al. 2023). Future studies may want to consider looking at age-related changes in auditory processing ability in individuals with mild TBI. Another limitation was the present study did not statistically account for time since mild TBI or number of mild TBIs because the primary interest was those who reported hearing-related difficulty following mild TBI. Further, the number of mild TBIs and time since last injury was collected via self-report. All individuals were outside of the post-acute range of three months, but number of mild TBIs and time since last mild TBI was variable. Future studies may want to consider using a more exact measure of time since injury when evaluating the variability within their results.

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