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Case Report

Hearing Difficulties as a Result of Traumatic Brain Injury

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Abstract

Background: Traumatic brain injury (TBI) has been shown to result in hearing difficulties (i.e., deficits in the processing of auditory information) without impacting pure-tone threshold detection. A missed diagnosis of hearing difficulties due to TBI because of normal hearing can lead to reductions in quality of life and missed opportunities to provide an appropriate treatment regimen.

Purpose: This study presents a case report of a female patient with a history of TBI due to a motor vehicle accident that resulted in a broad range of symptoms, including self-perceived hearing difficulties and poorer-than-normal auditory processing performance.

Research Design: Case report.

Study Sample: A 58-year-old woman with a history of a mild TBI due to a motor vehicle accident.

Data Collection: A neuro-audiology evaluation was conducted to address the patient's hearing complaints. The evaluation included standard audiometric and auditory processing test batteries.

Results: The case report focuses on the patient's history of TBI and her presentation to our clinic with hearing complaints. Her clinical audiological outcomes, including an auditory processing assessment, and treatment with mild-gain hearing aids are discussed. The use of mild-gain hearing aids resulted in improved auditory processing skills and a significant improvement in quality of life.

Conclusions: Patients with a history of TBI often have multiple and debilitating symptoms, including hearing difficulties. Accurate diagnosis of auditory processing deficits in the face of normal pure-tone detection abilities is essential to provide treatment options that can improve daily function and quality of life.

Key Words: Auditory processing, auditory rehabilitation, hearing aids, traumatic brain injury

Abbreviations: CANS = central auditory nervous system; FM = frequency modulated; GIN = Gaps-in-Noise; LOC = loss of consciousness; MLD = masking level difference; mTBI = mild traumatic brain injury; MVA = motor vehicle accident; PCS = postconcussive syndrome; R-SPIN = Revised Speech Perception in Noise; SNR = signal-to-noise ratio; TBI = traumatic brain injury

INTRODUCTION

Traumatic brain injury (TBI) is a disruption to the normal function of the brain and can be the result of a blow to the head, a penetrating head wound, or concussive blast-related injury (Gondusky and Reiter, 2005; Menon et al, 2010; Centers for Disease Control and Prevention, 2017). TBI is a leading cause of death and

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disability in the United States, with over seven million individuals experiencing a TBI per year (Taylor et al, 2017). The most common causes of TBI are falls, motor vehicle accidents (MVAs), being struck by an object or external force (e.g., assaults), and intentional self-harm (Taylor et al, 2017). MVA-related TBIs result in the third leading cause of emergency department visits and are the leading cause of hospitalizations (15- to 44-year-olds) and death (5- to 24-year-olds) (Taylor et al, 2017).

The symptoms associated with TBI are varied and usually depend on a number of factors, including the severity of the injury (mild to severe) and the status of the brain preinjury. Symptoms associated with TBI can include but are not limited to memory loss, psychosocial problems, sensory impairment, fatigue, headaches, poor attention, depression, sleep disturbances, dizziness, and loss of coordination (Centers for Disease Control and Prevention, 2017). Seventy-five percent of TBI cases are classified as mild (Langlois et al, 2006); however, it is reported that even those with a mild TBI (mTBI) have a risk of depression and experience emotional changes (Rau et al, 2010). Most individuals with an mTBI will recover within 3–6 months postinjury; however, some develop neuropsychiatric symptoms referred to as post-concussive syndrome (PCS) (Carroll et al, 2004). PCS is a disorder in which symptoms from TBI develop soon after an injury and persist for weeks to months post-injury, and is seen in about 60% of patients who have had minor head injuries without loss of consciousness (LOC) (Rowe and Carleson, 1980). Common PCS symptoms include tinnitus, dizziness, noise sensitivity, visual processing deficits, headaches, inattention, instability, and poor memory (Dischinger et al, 2009).

A common persistent complaint of patients with a history of TBI presented to audiologists is difficulty in communication, specifically hearing (e.g., trouble hearing in background noise, difficulty understanding rapid speech, and deficits remembering spoken directions or information) (Cockrell and Gregory, 1992; Bergemalm and Borg, 2001; Bergemalm and Lyxell, 2005; Lux, 2007; Oleksiak et al, 2012), despite normal pure-tone hearing. Persistent complaints of hearing difficulty are unsurprising, given that damage to the brain due to TBI includes those areas important for the perception of auditory information (i.e., the central auditory nervous system, CANS). Identifying a site of lesion within the CANS, however, is difficult because of the inconsistent presentation of TBI. Physiologically, potential damage to the CANS from TBI due to shear and stress waves from acceleration/deceleration injuries includes concussion, diffuse injury to blood vessels and axons, subdural hemorrhage, swelling, cell death, and/or disruption of inputs to and from brain stem auditory nuclei (Hurley et al, 2004; Taber et al, 2006). The shearing and stretching of structures can occur throughout the CANS, including the brain stem, cerebral cortex, and the corpus callosum, potentially disrupting auditory processing at any and all levels. Impairments and/or disruptions to the pathways within the CANS can result in hearing difficulties perceived by the patient.

The prevalence of hearing difficulties in patients with a history of TBI has been reported to be as high as 58% (Bergemalm and Lyxell, 2005). Although hearing difficulties do not occur in every individual with a history of TBI, they may be the patient's primary complaint. The recent focus on central auditory effects from mTBI among military personnel (e.g., Fausti et al, 2009; Gallun et al, 2012) and athletes in contact sports (Turgeon et al, 2011; Winkler et al, 2016) suggests that hearing difficulties are prevalent among young to middle-age adults with a history of head injury. Bergemalm and Lyxell (2005) found that 58% of adults (25–59 years) with closed head injuries demonstrated performance on tests of auditory processing consistent with that of those with hearing difficulties (i.e., abnormal performance for interrupted speech). More recently, Oleksiak et al (2012) found abnormalities in central auditory processing in 16% of veterans with mTBI. It is likely that estimates of hearing difficulties in the adult TBI population underrepresent the true prevalence, as adults comprise a population that typically presents with normal pure-tone hearing as assessed by a standard audiological evaluation without further auditory processing assessment.

Several studies have demonstrated the relationship between mTBI and central auditory dysfunction (Levin et al, 1989; Meyers et al, 2002; Musiek et al, 2004). Musiek et al (2004) presented a case study of a 41-year-old woman with an mTBI due to a fall from a horse. Results of audiometric threshold measures were normal, whereas results from an auditory processing test battery revealed abnormally low performance for competing sentences, dichotic digits, and compressed speech. Meyers et al (2002) measured dichotic word recognition (i.e., recognition of different auditory stimuli simultaneously presented to each ear) in a group of adults with a history of TBI. Patients were divided into groups based on the duration of LOC: mTBI (<1 hour of LOC), moderate TBI (1–7 days of LOC), and severe TBI (8+ days of LOC). Results revealed that the more severe the TBI, the greater the deficit in dichotic listening. Levin et al (1989) presented similar results for dichotic consonant–vowel recognition in 69 patients with closed head injury. Levin et al found that the degree of asymmetry in dichotic consonant–vowel recognition was directly related to the severity of head injury. As the severity of the head injury increased, so did the asymmetry in dichotic listening scores between ears. Asymmetry in dichotic speech recognition between ears is an indication of central auditory dysfunction and, more broadly, an indication of difficulty understanding speech in competitive listening environments.

Gallun et al (2012) measured auditory processing abilities in military personnel with a history of blast exposure. Participants had normal hearing sensitivity and good word recognition scores in quiet. Seventy-eight percent of participants, however, complained of problems understanding speech in noisy listening conditions. Results of behavioral measures of auditory processing revealed that 75% of blast-exposed participants exhibited performance outside the normal range on at least one test, whereas 17% exhibited abnormal performance on two or more of the tests. Turgeon et al (2011) examined the auditory processing abilities of athletes with a history of concussive injury. Results demonstrated significantly poorer performance across measures for the concussed group relative to a nonconcussed control group. In addition, 63% of concussed participants performed abnormally (>2 standard deviations from the mean) on at least one of the four measures, with one participant performing abnormally on all four measures. The results of the Turgeon et al study and the studies reviewed previously support the growing body of evidence that most of the patients with mTBI are likely to experience hearing difficulties (i.e., central auditory dysfunction).

There is currently no definitive treatment protocol for hearing difficulties, including hearing difficulties resulting from a TBI. Audiologic rehabilitation strategies such as auditory training (Musiek et al, 2004) and the use of frequency-modulated (FM) systems (Saunders et al, 2014) have been used as treatment options for patients with normal pure-tone thresholds and hearing difficulties due to TBI. Another treatment option for hearing difficulties includes the use of mild-gain amplification; however, this treatment approach has not been specifically described for the TBI population. The use of mild-gain amplification to treat hearing difficulties has been studied in both children (Kuk et al, 2008) and adults (Kokx-Ryan et al, 2016; Roup et al, 2018). Mild-gain amplification serves to enhance the listener's ability to hear high-frequency consonants and improve the signal-to-noise ratio (SNR) for the patient, thereby improving hearing and communication. Roup et al (2018) reported significant improvements in hearing handicap (self-perception of hearing problems) and speech-in-noise performance relative to baseline measures for a group of adults with hearing difficulties. Although not the primary objective of the study, half of the hearing aid trial participants reported a history of TBI. The results from Roup et al suggest that mild-gain amplification can be a successful treatment approach for some adults with central auditory dysfunction and normal hearing sensitivity, including those with a TBI.

The assessment, diagnosis, and treatment of patients with hearing difficulties due to TBI can be challenging, as auditory processing dysfunction is typically not captured by the traditional clinical audiological evaluation. Missed diagnosis of hearing difficulties due to TBI because of normal hearing test results can lead to reductions in quality of life, including mental health issues such as depression (Rau et al, 2010). The following case study of a 58-year-old woman with a history of mTBI due to an MVA illustrates the complexities of assessment, diagnosis, and treatment; the successful use of mild-gain hearing aids as a treatment option; and the interdisciplinary nature of working with a patient with post-TBI deficits in the auditory domain.

CASE REPORT

Case History

The following case history is based on a review of the patient's medical and audiology records, and interviews with the patient. The patient was a 58-year-old woman who was seen for an audiologic and central auditory processing evaluation 12 months after experiencing an mTBI due to an MVA. Informed consent was obtained from the patient to present her case. She was a passenger in a stopped vehicle when her car was struck from behind by a vehicle traveling at approximately 55 miles per hour. The patient did not experience a loss or alteration of consciousness during or following the accident. She was transported by ambulance to a hospital for evaluation; a brain and spine computerized tomography scan was completed. Results of the computerized tomography were reported as normal, and hospitalization was not required. In the days immediately following the accident, the patient began to experience several debilitating symptoms across multiple domains, including cognition (memory difficulties, loss of concentration, difficulty communicating, and generalized fatigue), vision (light sensitivity, blurred vision, and decreased visual perception ability), hearing (sound sensitivity, tinnitus, and trouble hearing in background noise), vestibular (dizziness and problems with balance), physical (headaches, nausea, insomnia, and pain in the back and neck), and emotional (anxiety, fear of driving, etc.). She reported that her symptoms were exacerbated by fatigue. Approximately four months after the accident, the patient was seen by a neurologist and was diagnosed with PCS and post-MVA cervical myalgia. Over the course of the following one to two years, the patient was evaluated by multiple professionals, including an audiologist (3rd author), to address her ongoing symptoms.

Neuro-Vision Evaluation

The patient was seen for a neuro-vision evaluation approximately eight months post-MVA because of ongoing visual symptoms. Her visual symptoms included decreased visual perception ability, blurred vision, light sensitivity, eye fatigue within minutes of reading, and an exacerbation of symptoms due to visual stimulation. The neuro-optometrist noted that the patient exhibited significant functional vision deficits and visual–vestibular dysfunction that are typical for post-mTBI. The patient was diagnosed with convergence insufficiency (i.e., difficulty with vision at near distances; McGregor, 2014), pursuit eye movement deficit (i.e., difficulty tracking a moving object; Barnes and Collins, 2008), and suspected visual information processing delay. Neuro-visual therapy integrated with sensorimotor processing therapy was initiated to regain visual efficiency. Thirty-five days postinitiation of therapy, improvements were noted in reading, driving, headaches (less frequent), better sleep, and an ability to write and talk (e.g., communicate) for longer periods of time. The neuro-visual therapy was continued with the goal of further improvements in visual efficiency.

Neuropsychology Evaluation

The patient was evaluated by a neuropsychologist approximately nine months post-MVA to rule out cognitive impairment related to the mTBI and possible posttraumatic stress disorder. The patient presented with multiple cognitive symptoms, including difficulty with short-term memory, attention, multitasking, decision-making, following a conversation, and becoming overwhelmed by complex tasks. The patient was evaluated with a standard neuropsychological test battery. Performance on the Mini-Mental State Examination, a screening test for cognitive impairment (Folstein et al, 1975), was normal (score 28/30). In addition, her performance was normal (i.e., average) across multiple domains, including intelligence, processing speech and executive functioning, learning and memory, language, fine motor, and simple visuospatial reproduction. The neuropsychologist noted, however, that the patient became emotionally distressed during some of the testing, which may negatively impact her cognitive efficiency. The patient was diagnosed with PCS and posttraumatic stress disorder. Before this evaluation, the patient had been engaged in psychotherapy. The neuropsychologist recommended that she continue participating in psychotherapy to promote effective coping skills.

Audiological and Auditory Processing Evaluation

The patient was referred for a neuro-audiology evaluation to address her hearing complaints. She was seen for an audiological and auditory processing evaluation one year post-mTBI. She reported that she had no hearing or listening problems before the MVA, but since the accident had been experiencing sound sensitivity and difficulties hearing in background noise. The patient reported a significant negative impact of sound sensitivity issues on her daily life, including being unable to attend church, family events, difficulty hearing in a restaurant setting, and having difficulty in groups of people due to her perception of sounds being too loud. She reported considerable emotional distress related to her growing isolation and stated that she had been " robbed of life."

The audiological evaluation consisted of (a) otoscopy (visualization of the ear canals and tympanic membranes), (b) tympanometry (measure of middle-ear function), (c) acoustic reflex thresholds (measure of neural integrity), (d) pure-tone air and bone conduction thresholds (sound detection measurement), (e) speech recognition thresholds (softest level speech is recognized), (f) word recognition performance in quiet (percent correct of words recognized), and (g) speech-in-noise performance using the Quick Speech-in-Noise test (Killion et al, 2004). All audiometric equipment were calibrated according to the appropriate (ANSI, 2010; 2012). As part of the audiological evaluation, the patient completed two subjective questionnaires, the Hyperacusis Questionnaire (Khalfa et al, 2002) and the Hearing Handicap Inventory for Adults (Newman et al, 1990). Hyperacusis is an auditory phenomenon in which individuals experience increased sensitivity to sound. The Hyperacusis Questionnaire is a 23-item questionnaire that asks about the patient's loudness perception of everyday sounds. In addition, the Hyperacusis Questionnaire asks patients to report how often they experience a variety of physical symptoms related to hyperacusis (e.g., headaches, strong smells, and balance problems). The Hearing Handicap Inventory for Adults is a 25-item questionnaire designed to measure self-perceived handicap due to a "hearing problem" (e.g., "Does a hearing problem cause you to avoid groups of people?"). Scores range from 0 to 100, with higher scores indicating greater self-perceived hearing handicap.

An auditory processing evaluation was completed following the audiological evaluation. The auditory processing evaluation comprised the following tests: (a) the SCAN-3:A Tests for Auditory Processing Disorders in Adolescents and Adults (Keith, 2009); (b) 1-, 2-, and 3-pair dichotic digit recognition performance (Strouse and Wilson, 1999); (c) the Gaps-in-Noise (GIN) test (Musiek et al, 2005); (d) the 500-Hz masking level difference (MLD) test (Wilson et al, 2003); and (e) the Revised Speech Perception in Noise (R-SPIN) test (Bilger, 1984).

The SCAN-3:A includes five subtests that measure different aspects of auditory processing ability. The subtests include filtered words (monosyllabic words low-pass filtered at 1000 Hz), auditory figure-ground (monosyllabic words presented in competing babble to the same ear at a 0-dB SNR), competing words (monosyllabic words presented simultaneously to each ear, e.g., dichotic listening), competing sentences (two different sentences presented simultaneously to each ear, e.g., dichotic listening), and time-compressed sentences.

One-, two-, and three-pair dichotic digit recognition was measured using the Dichotic Digit Test from the *Tonal and Speech Materials for Auditory Perceptual Assessment*, Disc 1.0 (Department of Veterans Affairs, 1998). Briefly, the DDT is a 54-item test including one-, two-, and three-pair digits (1–10, excluding the bisyllabic 7). Dichotic digit recognition was assessed in both the free and directed recall response conditions. The patient was instructed to repeat all the numbers she heard in the free recall condition. In the directed recall right conditions, she was instructed to repeat all the numbers she heard in her right ear only. Similarly, she was instructed to repeat all the numbers she heard in her left ear only for the directed recall left condition. Recognition performance was based on the percentage of digits repeated correctly for each ear.

Temporal processing was assessed using the GIN (Musiek et al, 2005) and 500-Hz MLD tests (Wilson et al, 2003). The GIN test is a clinical test of temporal resolution where listeners are asked to detect when a gap, or silent interval, is present in a noise burst. There are a total of 36 noise bursts. Each noise burst contains zero to three silent gaps, with the length of the gap varying from 2 to 20 msec. The patient was asked to push a button every time she perceived a gap. There are two possible scores for the GIN test: percent of correctly identified gaps and the gap threshold, or the shortest gap identified at least four of six times. The 500-Hz MLD test assesses the listener's ability to take advantage of phase differences between ears when listening for a 500-Hz tone embedded in a 500-Hz noise burst. The test consists of two conditions: the S_0N_0 condition, in which the 500-Hz signal (S) and the 500-Hz noise burst (N) are both in phase between ears, and the $S_\pi N_0$ condition, in which the 500-Hz signal is out of phase between ears while the noise burst is in phase between ears. The threshold of the 500-Hz signal is determined relative to the level of the noise for each condition, and the difference between the two thresholds (S_0N_0 and $S_\pi N_0$) is considered the MLD.

Finally, speech perception in noise was assessed with the R-SPIN test (Bilger, 1984). The R-SPIN test consists of 200 sentences that vary according their contextual content. Half of the sentences are considered high predictability (e.g., Stir your coffee with a *spoon*), in that the final key word is predictable based on the context of the sentence. The other half of the sentences are considered low predictability (e.g., She thought about the *spoon*), in that the final key word is not predictable based on a lack of context in the sentence. The patient was instructed to repeat the final word of each sentence. Recognition performance was based on the percentage of key words repeated correctly.

Results of the Audiological and Auditory Processing Evaluations

Results from the audiological evaluation revealed normal otoscopy bilaterally, tympanometry (i.e., middle-ear function) within normal limits bilaterally (Wiley et al, 1996), and presence of acoustic reflex thresholds bilaterally.

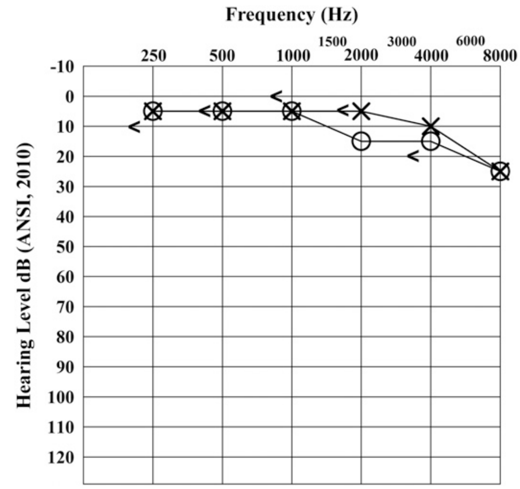

Figure 1. Pure-tone audiogram for the patient from May 11, 2015. Air conduction thresholds for right (circles) and left ears (x's) are presented for all octave frequencies (250–8000 Hz). Bone conduction thresholds for the right ear (<) are presented for 250–4000 Hz.

Figure 1 presents the patient's pure-tone audiogram, which revealed normal pure-tone thresholds bilaterally (thresholds ≤ 25-dB HL). Word recognition scores (CID W22 in quiet) were excellent in the right (92%) and left (100%) ears. Results of the Quick Speech-in-Noise test measured binaurally in sound field revealed a mild SNR loss of 6.5 dB (Killion et al, 2004).

Results of the Hyperacusis Questionnaire revealed that sounds typically reported as moderately loud by most individuals were reported by the patient as constantly too loud. In fact, every sound on the list was reported as being too loud for the patient, ranging from the vacuum cleaner to music in grocery stores. Similar to the results of the Hyperacusis Questionnaire, the patient presented with a substantial hearing handicap (score = 96 out of 100). The patient indicated that all but one scenario (e.g., feeling frustrated or embarrassed) on the Hearing Handicap Inventory for Adults was caused by a "hearing problem." Results from both questionnaires revealed substantial self-perceived hearing difficulties as a direct result of the mTBI that were having a negative impact on her quality of life.

Results from the SCAN-3:A revealed age-appropriate auditory processing skills in the areas of auditory closure (filtered words), auditory figure-ground (speech-in-noise), binaural separation (competing sentences), and temporal processing (time-compressed sentences). By contrast, the patient exhibited abnormally low performance for competing words, or binaural integration, scoring in the 5th percentile. Binaural integration, or dichotic listening, skills assist with localizing sound and listening to a targeted message when competing information is also present in the environment.

Results of 1- and 2-pair dichotic digit recognition revealed near-ceiling performance (i.e., near 100%);

however, results for the three-pair dichotic digits were similar to those of the SCAN-3:A. Three-pair dichotic digit recognition performance was normal (Strouse and Wilson, 1999) on digits presented to the right ear for free recall (83.3%) and directed recall (100%). By contrast, the patient exhibited below normal recognition performance (Strouse and Wilson, 1999) on digits presented to the left ear for free recall (46.3%) and directed recall (85.2%). Poor performance on dichotic listening tasks, especially in the left ear, is consistent with central auditory dysfunction and likely contributed to the patient's hearing difficulties.

Results of temporal processing measures revealed a 500-Hz MLD (12 dB) within normal limits (Wilson et al, 2003), and normal gap detection abilities (GIN test) for the right ear (60% gaps correctly identified, gap threshold of 6 msec) (Musiek et al, 2005). By contrast, the patient exhibited abnormally poor gap detection abilities for the left ear (50% gaps correctly identified, gap threshold of 8 msec) (Musiek et al, 2005). Poor gap detection abilities, or poor auditory temporal resolution, can contribute to difficulty understanding speech, particularly in noisy environments.

Finally, results from the R-SPIN test at a 0-dB SNR revealed excellent speech-in-noise abilities for high-predictability sentences (100% in the sound field). By contrast, the patient exhibited abnormally poor performance for low-predictability sentences (64% in the sound field) (Roup et al, 2018). The R-SPIN test results demonstrate the importance of contextual cues when listening in a noisy environment (e.g., excellent performance on high-context sentences and poor performance on low-context sentences). Poor speech-in-noise recognition performance on low-predictability sentences is consistent with the patient's primary complaints of difficulty understanding speech in noisy environments.

Based on the patient's self-reported communication and hearing difficulties, and the results of the audiometric and auditory processing evaluations, a number of recommendations were made. The patient was referred to the OSU Speech-Language-Hearing Clinic to address her communication difficulties. She was also referred to the Department of Otolaryngology for vestibular assessment to address her reports of dizziness and lightheadedness. The patient had reported wearing earplugs because of her sound sensitivity issues (i.e., hyperacusis). It was recommended that she set a goal to stop wearing the earplugs, as they exacerbate hyperacusis and interfere with desensitization. Finally, audiologic rehabilitation was recommended (discussed in the following paragraphs) to address her ongoing hearing difficulties.

Speech-Language, Vestibular, and Neuro-Otology Assessments

The patient was evaluated by a speech-language pathologist for communication difficulties approximately 23 months post-MVA. The patient's speech and language abilities were assessed with the Repeatable Battery for the Assessment of Neuropsychological Status (Randolph et al, 1998) test, which includes measures of the fluent use of expressive and receptive language, and functional communication measures. Results of the Repeatable Battery for the Assessment of Neuropsychological Status revealed mild cognitive-communication deficits, characterized by decreased immediate recall and decreased attention in sensory stimulating environments. Therapeutic goals were discussed and implemented, including completion of moderately complex language tasks in auditory simulating environments, completion of activities to improve short-term recall in auditory stimulating environments, and implementation of strategies at home to manage attention, memory, and mental fatigue.

A vestibular assessment was also completed by an audiologist in the Department of Otolaryngology approximately 23 months post-MVA. Results of the assessment (video nystagmography) were normal. The audiologist referred the patient to neuro-otology to address her complaints of dizziness/vertigo. The patient was seen by a neuro-otologist the following week. An MRI was ordered; the results were unremarkable. Based on her ongoing vestibular complaints along with concerns regarding perceived balance deficits when driving, the patient participated in physical therapy focused on vestibular issues. She was also evaluated in the driving simulation laboratory at the Ohio State University. The patient reported improvement in overall balance and driving following treatment, along with greater confidence in driving.

Audiologic Rehabilitation

Strategies aimed at improving the patient's hearing difficulties and communicative function, with the ultimate goal of improving her quality of life, were discussed with the patient. Rehabilitation strategies discussed included auditory training (Sweetow and Sabes, 2006; Murphy et al, 2011; Figueiredo et al, 2015) and mild-gain amplification (Kuk et al, 2008; Roup et al, 2018). The patient chose to pursue mild-gain amplification as a means of improving her speech understanding and decreasing her listening effort.

The patient was fit bilaterally with receiver-in-the-canal, wide dynamic range compression digital hearing aids. The hearing aids were coupled to the patient's ears with open domes to ensure maximal comfort and minimal occlusion of the ear canals. The hearing aids were enabled with adaptive multiband directional microphones and multiband noise reduction. When listening in a noisy environment (i.e., a poor SNR), the multiband directionality and noise reduction features worked to improve the SNR and listening comfort for the patient. The hearing aids were set to provide mild (5–15 dB) levels of gain

Table 1. Patient's Hearing Aid Insertion Gain Values (in dB) for 1000–4000 Hz for Right and Left Ears

	Frequency in Hz			
	1000	2000	3000	4000
Mean				
Right ear	5	10	14	10
Left ear	5	10	14	10

(i.e., amplification) for the patient in the mid- to high-frequency range for soft and conversational inputs. Verification of hearing aid gain was accomplished using real-ear probe microphone measures (Frye Fonix 7000; Frye Electronics, Beaverton, OR). A specific target was not used. Rather, the ANSI-weighted digital speech signal (ANSI, 2017) was used to measure real-ear insertion gain for two inputs (65- and 90-dB SPL) relative to the patient's real-ear unaided responses. Programming software was used to adjust the frequency response of the hearing aids to provide approximately 5–15 dB of gain between 1000 and 4000 Hz. Table 1 presents the insertion gain values for the patient's right and left hearing aids. In addition, electroacoustic front-to-back ratio verification confirmed a reduction in the level of noise relative to the speech signal for the multiband directionality feature. Maximum output of the hearing aids did not exceed 100-dB SPL for any frequency. The patient was counseled regarding the use and care of the hearing aids during a 1-hour orientation session.

During the first week post–hearing aid fitting, the patient reported wearing the hearing aids for approximately four to eight hours a day and stated that listening in quiet situations was worse with the hearing aids. Given the patient's normal detection abilities and excellent recognition performance in quiet, as well as her loudness tolerance issues, it is not surprising that she found using the hearing aids in quiet bothersome at first. By contrast, the patient reported substantial improvements when listening in noisy environments. She stated that she could now follow conversations easier. About a month following the initial hearing aid fitting, the patient was wearing the hearing aids 12–14 hours a day, consistently reported that the hearing aids "helped a lot" in quiet environments, could understand speech in background noise, attended multiple group meetings, found soft and loud sounds to be tolerable, and no longer avoided noisy environments. She reported being very satisfied with her hearing aids, stating that they allowed her to participate in activities she previously enjoyed.

During her 1-month follow-up appointment, the patient completed an aided Hearing Handicap Inventory for Adults questionnaire and aided speech-in-noise testing. Figure 2 presents unaided and aided Hearing Handicap Inventory for Adults scores. As seen in Figure 2, the patient's hearing handicap score decreased drastically from a pretreatment (unaided) score of 96 to a posttreatment (aided) score of 20. The reduction in hearing handicap demonstrates a clear improvement in her perception of how her hearing difficulties were impacting her social and emotional well-being. In addition, the patient completed aided speech-in-noise testing during the follow-up appointment. Before testing, a hearing aid check was completed to ensure proper functioning. Figure 3 presents unaided and aided R-SPIN recognition performance at 0-dB SNR. The benefit of the hearing aids is clearly demonstrated by the improvement in recognition performance for the low-predictability sentences. The patient exhibited a 24% improvement in her ability to recognize words without any contextual cues.

The patient has been seen for routine follow-up care on a regular basis since the initial hearing aid fitting protocol was completed. Follow-up appointments have included hearing aid checks with minor adjustments to the programs related to listening comfort, and a repeat audiometric evaluation. No changes in pure-tone detection thresholds were noted, and word recognition in quiet abilities remains excellent (96–100%). An additional recommendation of an FM system to improve listening in noise was made to address her residual hearing difficulties; however, the patient declined to pursue FM technology at the time. The patient continues to report substantial improvements in self-perception of her hearing difficulties and continued satisfaction with her hearing aids.

DISCUSSION

The case study presented in this report illustrates two key issues: (a) hearing difficulties can present as one of the primary and most debilitating symptoms post-TBI and (b) effective treatment strategies such as mild-gain hearing aids are available for patients with a history of TBI who experience hearing difficulties.

The audiologic symptoms experienced by this patient are consistent with a growing body of evidence detailing the hearing difficulties (i.e., auditory processing dysfunction) that are prevalent among patients with a history of TBI, despite a diagnosis of normal pure-tone detection abilities (i.e., "normal hearing") (Cockrell and Gregory, 1992; Bergemalm and Borg, 2001; Bergemalm and Lyxell, 2005; Lux, 2007; Oleksiak et al, 2012; Saunders et al, 2014). This patient presented to our audiology clinic one-year post-TBI with substantial

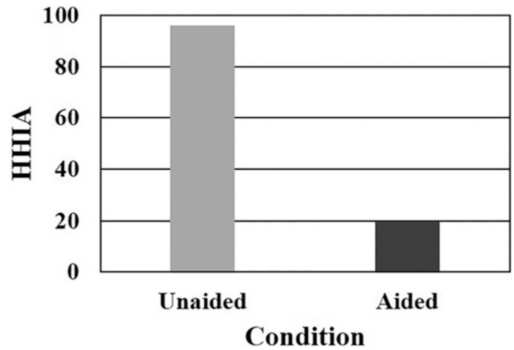

Figure 2. Scores for the Hearing Handicap Inventory for Adults are presented as a function of hearing aid condition: unaided (light gray bars) and aided one-month post–hearing aid fitting (dark gray bars).

self-perceived hearing difficulties, including sensitivities to loud sounds and difficulties hearing in background noise, that were preventing her from fulfilling her normal daily activities. Results of the standard clinical audiometric assessment, however, revealed normal results for pure-tone detection and speech understanding in quiet. The conflict between her self-perceived hearing difficulties and the standard audiometric test results provided an opportunity for further evaluation. Results of the auditory processing test battery revealed abnormally low performance on multiple auditory processing measures, including dichotic listening, speech in noise, and temporal processing. Deficits across these auditory domains provided clinical evidence that both supported the patient's self-perception of her hearing difficulties and provided a basis for the provision of audiological treatment recommendations.

A definitive treatment protocol for hearing difficulties does not currently exist. Our own clinical experience and recently published research (i.e., Roup et al, 2018), however, provide an evidence-based rationale for our recommendation of mild-gain amplification for

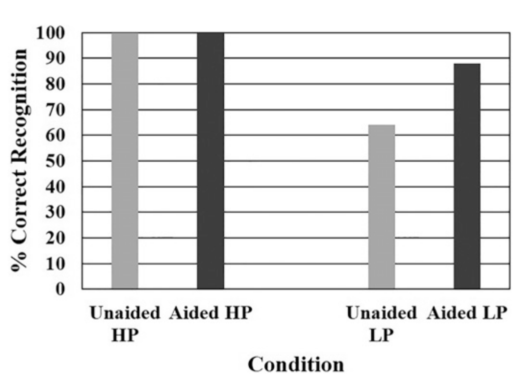

Figure 3. R-SPIN recognition performance (in % correct) for the patient as a function of hearing aid condition: unaided (light gray bars) and aided one-month post–hearing aid fitting (dark gray bars) are presented for high-predictability and low-predictability sentences at a 0-dB SNR.

this patient. The use of mild-gain amplification to treat hearing difficulties serves two purposes: (a) to enhance mid- to high-frequency low-intensity speech sounds that are essential to speech understanding and are often masked by more intense background noise and (b) to increase listening comfort through digital signal processing with adaptive directionality and noise reduction, both of which serve to improve the SNR when listening in noisy environments. For patients with post-TBI hearing difficulties, a recommendation to trial mild-gain amplification is, therefore, warranted. After a four-week trial, this patient reported substantial improvements in her perception of her hearing abilities, particularly when using the hearing aids in noisy environments. In addition, she exhibited significant improvements in self-perceived hearing handicap (see Figure 2) and speech-in-noise performance for low-context stimuli (see Figure 3). The patient continues to be a successful hearing aid user three years post-TBI. She does, however, continue to experience hearing difficulties and often describes herself as "deaf in background noise" without her hearing aids.

Another key issue elucidated by this case is the interdisciplinary nature of medical treatment often needed for patients with a history of TBI. Patients who experience a TBI often report symptoms across multiple domains, including hearing and communication (Isaki and Turkstra, 2000; Bergemalm and Borg, 2001; Bergemalm and Lyxell, 2005; Oleksiak et al, 2012). This patient was no exception, having received evaluation and treatment from multiple health-care professionals, including neurology, neuropsychology, neuro-optometry, speech-language pathology, and audiology. Interdisciplinary care for this patient was vital to her recovery and improvement in quality of life post-TBI.

CONCLUSIONS

The case report presented here illustrates the negative impact of hearing difficulties that can arise as a result of TBI, and the positive impact of an auditory processing assessment and treatment protocol on post-TBI quality of life. Clearly, clinical audiology has a role to play on the interdisciplinary team and an opportunity to provide care to those individuals who experience TBI-induced hearing difficulties. Assessment procedures beyond the standard clinical audiometric evaluation are available and have been shown to identify deficits in auditory processing that corroborate a patient's self-perceived hearing difficulties. In addition, treatment options, such as mild-gain hearing aids, can be successfully implemented to provide substantial benefit to patients who experience hearing difficulties due to TBI, even in the presence of "normal" pure-tone detection abilities. It is important to note that this patient was both willing and motivated to trial mild-gain amplification. Our clinical experience and results from the Roup et al mild-gain amplification trial, however, demonstrate that not all patients with self-perceived hearing difficulties (with or without a history of TBI) experience benefit from amplification, and motivation or lack of motivation to use technology can be a key factor in the success of such trials.

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