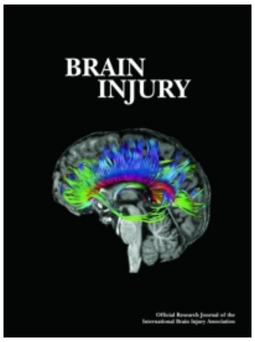

Brain Injury

ISSN: 0269-9052 (Print) 1362-301X (Online) Journal homepage: http://www.tandfonline.com/loi/ibij20

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BRAIN INJURY
https://doi.org/10.1080/02699052.2018.1447686

Difficulty hearing in noise: a sequela of concussion in children

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ABSTRACT

Objective: Concussions can result in auditory processing deficits even in the absence of hearing loss. In children and adolescents, the extent to which these impairments have functional consequences for everyday listening, such as the ability to understand speech in noisy environments, is unknown.
Research design: Case-control study.
Subjects and methods: Forty youth comprised the participants: 20 had sustained a concussion and were recovering from their injury, and 20 controls had sustained non-concussive orthopaedic (e.g. musculoskeletal) injuries. All were evaluated on the Hearing in Noise Test, an audiologic index of the ability to hear sentences in adverse listening conditions.
Results: Children and adolescents recovering from concussions demonstrated an overall impaired ability to perceive speech in noisy backgrounds compared to a peer control group. This deficit also emerged across trials in the most taxing listening condition, and with respect to published, age-normative values.
Conclusions: Functional listening skills—such as the ability to understand speech in noise, and the ability to sustain performance over time in taxing auditory conditions—may be compromised in children with concussions. These impairments may exacerbate cognitive and academic challenges associated with concussion injuries, and should be considered in return-to-learn and return-to-play decisions.

ARTICLE HISTORY
Received 6 November 2017
Revised 17 February 2018
Accepted 27 February 2018
Published online 10 March 2018

KEYWORDS
Concussion; post-concussion syndrome; auditory processing; speech-in-noise perception; mild traumatic brain injury

Introduction

Over 430,000 children in the U.S. are hospitalized for traumatic brain injuries (TBIs) each year, and mild TBIs, or concussions, represent the most prevalent injury type (1,2). Of these cases, an estimated 25% result in symptoms lasting 2 or more weeks. This persistent constellation of cognitive, emotional, and physical symptoms interferes with emotional well-being and quality of life (3). Persistent concussion symptoms can also have detrimental effects on learning and academic performance (4), which we propose may be due, in part, to auditory processing difficulties. Educational environments can be chaotic, distracting, (5) and noisy (6), and thus necessitate competency in auditory processing. Despite the importance of auditory processing for classroom learning and evidence for auditory sequelae in post-concussion syndrome (7), the hypothesis that concussion-related auditory processing impairments contribute to academic struggles for children with concussions is understudied.

Accumulating evidence suggests auditory processing deficits result from concussions in adults. Turgeon et al. studied college athletes who had sustained a concussion and found that over half demonstrated impairments in at least one of four auditory processing tests (i.e. speech perception in quiet, dichotic listening ability, monaural separation, and tone pattern recognition) compared to control peers (8). Another investigation comparing adult patients with persistent concussion symptoms to a control cohort on several auditory processing tests (i.e. gaps in noise, temporal processing, binaural masking level difference, and time compressed speech) found the individuals with concussions were more likely to perform abnormally on these tests (7). Moderate TBI has been found to result in deficits on tests of distorted speech discrimination and sound localization, and these deficits lasted 7–11 years after a head injury in 58% of the participants (9). In Veterans and Service Members who sustain blast-induced TBIs, auditory dysfunction can manifest even in the presence of 'normal' hearing thresholds (10). This growing body of work, reviewed in Gallun et al., demonstrates the deleterious effects of TBI on central auditory processing through self-report, behavioural, and electrophysiological evidence (11). In terms of TBI-induced auditory processing deficits in the paediatric population, one investigation showed 16% of children admitted to a rehabilitation unit for a moderate or severe TBI performed poorly on an auditory processing test involving low-redundancy speech (12). Our group previously reported evidence of auditory neurophysiological impairments following a concussion in children and adolescents (13); these findings were replicated in adults shortly thereafter (7,14). This work suggests auditory processing is an additional neurosensory domain that can be affected by concussions, similar to

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visual, motor, and vestibular functions (15,16). However, whether or not there are functional consequences for these impairments—such as the ability to hear in noise—has not yet been studied in children with concussions.

While the aforementioned studies implicate auditory processing is affected by concussion, only a few explicitly tested hearing in noise ability. Auditory-related complaints, such as difficulty listening in background noise, remembering and following oral instructions, and understanding rapid or degraded speech, have been reported by a number of patients with concussions (17) and Service Members and Veterans with TBI (11). Experimental investigations examining speech-in-noise processing are again, limited to the adult population. For example, Gallun and colleagues reported blast-exposure injuries incur widespread consequences for auditory processing in military Service Members, including difficulty with speech-in-noise perception (18). This result was replicated in a separate group of service members with a different test of hearing in noise (10). For civilians with concussions, one investigation demonstrated adults, ages 19–61, with persistent concussion symptoms perform abnormally on the ability to perceive words in noise relative to controls (7). Hoover and colleagues replicated this finding by showing perception of words—and sentences—is impaired in 84% of a concussion group versus 9% of controls (19).

To our knowledge, no study to date has investigated speech-in-noise perception following a concussion in a paediatric population, especially in children with symptoms lasting 2 weeks or longer. Considering the importance of speech-in-noise perception for classroom learning and that concussion can adversely impact academic performance, there is reason to believe that concussions, which alter neurophysiological integration and cognitive function, also impair this essential listening strategy. Identifying the extent of this impairment in children with concussions is a vital first step for understanding whether auditory dysfunction is a contributor to the adverse academic outcomes in this population. In addition, this work may have profound implications for helping students 'Return to Learn' (20) by driving development of therapeutic interventions for children with auditory processing deficits that manifest because of a concussion.

The main objective of this research was to determine the functional consequences of auditory processing impairments in youth with concussions. We tested the hypothesis that auditory physiologic disruption after a concussion has implications for real-world listening (i.e. the ability to hear in noisy environments), and predicted that this ability would be impaired in individuals with concussions.

Methods

Participants

Patients presented to a tertiary care clinic for care of concussion or musculoskeletal injuries and were eligible for recruitment if they were monolingual-English speakers with no history of a neurological disorder. Controls patients were also eligible if they had no history of a concussion. Patients were excluded if they showed structural abnormalities on neuroimaging or failed to pass a peripheral hearing screening at the outset: normal otoscopy and distortion product otoacoustic emissions ≥6 dB sound pressure level (SPL) above the noise floor from 0.5 to 4 kHz.

Parents/legal guardians provided informed consent and children provided informed assent. The Institutional Review Boards of Northwestern University and Ann and Robert H. Lurie Children's Hospital approved all procedures, and participants were monetarily compensated for their time.

Procedures

Concussion diagnosis was consistent with guidelines set by the Centers for Disease Control and Prevention (21) and the Zurich consensus statement (22). Post-concussion symptoms were assessed using the Post-Concussion Symptom Scale (PCSS), a Likert-scale checklist that asks the participant to grade their symptom from 0 (not present) to 6 (severe) (23). The PCSS is scored by adding the degree of intensity for each symptom, and the total score reflects the individual's symptom load. Group demographics such as age, sex, and socio-economic status were compared using descriptive statistics. To index socio-economic status, a zip-code analysis was performed whereby median household income for each zip code was pulled from 2015 census data (24).

The two patient groups (concussion and control) were tested on their ability to hear in noisy backgrounds using the Hearing in Noise Test (HINT) (25), an audiological measure of speech-in-noise processing. In this test, participants are asked to repeat back sentences presented in speech-shaped background noise. Sentences are semantically and syntactically simple and correct (Bamford–Kowal–Bench corpus) (26) and contain vocabulary appropriate for a first-grade reading level (e.g. 'Sugar is very sweet'). Sentences are presented through Sennheiser HD 25-1 headphones at adaptive levels in noise that is fixed at 65 dB SPL. A detailed explanation of the standard HINT adaptive procedure is explained elsewhere (25). The outcome variable, threshold signal-to-noise ratio (SNR), is defined as the dB SNR difference between the speech dB level and noise dB level in which the participant obtains 50% correct sentence repetition. A lower threshold indicates a greater ability to perceive speech in adverse listening conditions.

In this study, HINT performance was tested under different listening conditions: co-located in space (noise and sentences to both ears), and separated in space (noise to left ear, sentences in both; noise to right ear, sentences in both). Because test performance was identical for the two spatially separated conditions, we created a composite average of the two, 'spatially separated', which is displayed in the figures. All statistics were performed across the three different conditions, however.

To compare performance of the two patient groups across the listening conditions, a 2 (group) × 3 (listening condition) repeated measures analysis of covariance (RMANCOVA) was used with age as a covariate. Trial-by-trial performance trajectories were quantified and compared with three 2 (group) × 11 (trial) RMANCOVAs, one for each listening condition. To compare concussion and control HINT performance to national averages, percentile performance values were taken from Soli and Wong (27); percentile values are based on performance for each participant's age at test. All statistics were computed using SPSS (IBM Corp.).

Results

Participant characteristics

Forty youth comprised the sample (M = 13.56 years, SD = 1.89 years, Range = 8.16–16.5 years)(Table 1). Twenty individuals were included in the concussion group (M = 13.70 years, SD = 1.79 years, 14F), and 20 individuals made up the orthopaedic control group (M = 13.42 years, SD = 2.03 years, 16F). The groups were balanced for age ($t(38) = -0.45$, $p = 0.66$) and sex distribution ($X^2(1) = 0.53$, $p = 0.46$). Also, socioeconomic status—indexed by the average median income at each participant's zip code—did not differ between the groups ($t(38) = 0.82$, $p = 0.42$).

Participants in the concussion group were visiting the clinic for management of prolonged symptoms; therefore, most (18 out of 20) were symptomatic at test (PCSS M = 31.5, SD = 21.9, Range = 0–71; the two patients who were not symptomatic had not returned to baseline performance on their ImPACT test). The most frequently reported symptoms were 'headache' (17 out of 20), 'difficulty concentrating' (16 out of 20), 'drowsiness' (14 out of 20) and 'sensitivity to light' (14 out of 20). Concussion injuries were attributed to accidents in sports, including cheerleading (n = 2), football (3), hockey (2), basketball (1), soccer (1), softball (2), volleyball (1), and non-sport activities (8). On average, children were tested 27 days after their injury (M = 26.7 days, SD = 15.3 days, Range = 5–56 days). Thirteen out of 20 had a prior history of concussion, with six of these prior injuries occurring within 1 year of test. Five reported a diagnosis of a learning disability, and four reported a diagnosis of anxiety. Within-group comparisons of HINT performance showed no significant effects of recovery time (≥30 days since injury (n = 9)) vs. <30 days since injury (n = 11)), prior history of concussion (no history (n = 7), prior history, >1 year (n = 7) and prior history, <1 year (n = 6)) or learning disability (diagnosis (n = 5) vs. no diagnosis (n = 15)). Please see Table 2 for within-group comparisons.

Participants in the control group were being treated for musculoskeletal injuries and none reported a prior history of concussion, nor diagnosis of learning disability, anxiety, or depression. Injures included apophysitis of iliac crest (n = 1); back contusion (1); bilateral paraesthesia (1); contusion of right lower leg (1); hip strain/pain (2); foot pain (1); low back sprain (1); low back strain (1); toe pain/osteonecrosis (1); patellofemoral arthralgia (1); patellofemoral pain syndrome (4); plantar fasciitis (1); rotator cuff tendonitis (1); Sever's apophysitis (1); spondylolysis, lumbar region (1); and winged scapula (1). Injuries were attributed to badminton (n = 1), baseball (1), basketball (3), cross-country/track (1), dance (4), diving (1), gymnastics (2), hockey (1), ice skating (1), soccer (1), swimming (1), tennis (1), and other recreational activities (2).

Children with concussion perform more poorly than controls on HINT

Across listening conditions, the individuals in the concussion group performed worse than controls (Figure 1; ME of Group: $F(1,37) = 14.48$, $p < 0.001$; Condition × Group IXN: $F(1,36) = 0.28$, $p = 0.76$)). Age was used as a covariate due to its significant effect on HINT performance across listening conditions (ME of age: $F(1,37) = 10.26$, $p = 0.003$).

Table 1. Descriptive statistics for the two patient groups: concussion and control.

	Mean age (SD)	Sex	Zip code 'median household income'	History of previous concussion(s)	Learning disability	Anxiety
Concussion (n = 20)	13.70 (1.79)	14F, 6M	$87,160	13	Personal history: 5	Personal history: 4
Control (n = 20)	13.42 (2.04)	16F, 4M	$96,193	0	0	0
	$t(38) = -0.45$ $p = 0.66$	$X^2(1) = 0.53$ $p = 0.46$	$t(38) = 0.82$ $p = 0.42$			

Means are reported with standard deviations.

Table 2. Within-concussion-group comparisons for recovery time (days since injury), prior history of concussion, and learning disability diagnosis.

		Co-located performance (dB SNR)	Spatially separated performance (dB SNR)
Days since injury	<30 days (n = 11)	−1.23 (1.33)	−7.84 (0.88)
	≥30 days (n = 9)	−0.96 (2.16)	−7.28 (1.39)
		$t(18) = -0.34$, $p = 0.73$	$t(18) = -1.08$, $p = 0.29$
Prior history of concussion	No (n = 7)	−.543 (2.04)	−6.84 (1.16)
	Recent (within 1 year) (n = 6)	−1.76 (1.61)	−7.87 (0.80)
	Not recent (>1 year) (n = 7)	−1.13 (1.44)	−8.10 (1.09)
		$F(2,17) = 0.81$, $p = 0.46$	$F(2, 17) = 2.84$, $p = 0.08$
Learning disability	No (n = 15)	−1.06 (1.92)	−7.75 (1.11)
	Yes (n = 5)	−1.28 (0.96)	−7.13 (1.24)
		$t(18) = 0.24$, $p = 0.81$	$t(18) = -1.05$, $p = 0.31$

Means are reported with standard deviations.

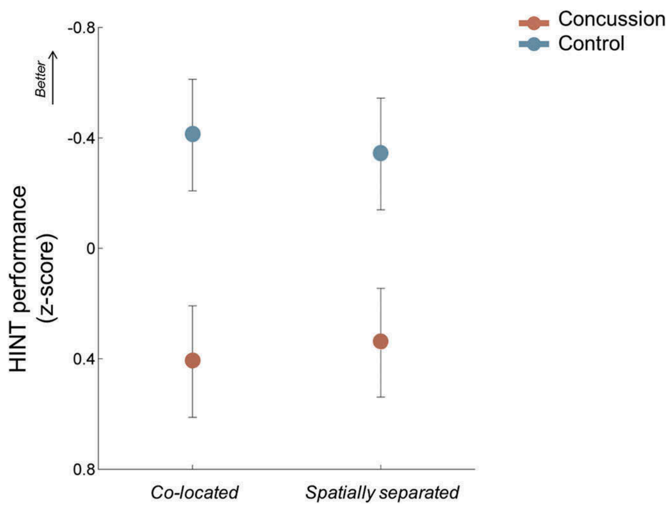

Figure 1. HINT performance for individuals in the concussion (orange) and control (blue) groups. *Z*-scores were computed based on the participants tested in this sample (n = 40). A higher number reflects better performance. 'Co-located' refers to the listening condition in which speech and noise are presented together in space, while 'spatially separated' refers to an average of the conditions in which speech and noise are separated in space. Error bars represent +/- 1 standard error of the mean.

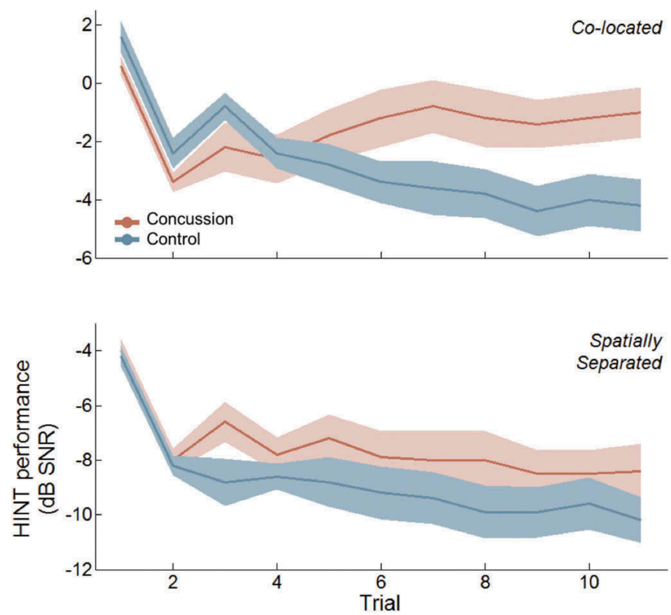

Figure 2. Trial-by-trial performance for the HINT is plotted for concussion (orange) and control groups (blue). A lower dB SNR indicates a greater ability to perceive speech in adverse listening conditions. In the 'co-located' condition, while the performance for the control group steadily improves, performance for individuals in the concussion group steadily worsens. In contrast, for the 'spatially separated' condition, performance for both groups steadily improves over time. Shading represents +/- 1 standard error of the mean.

Concussion group performance on HINT degrades over time in the more difficult listening condition (co-located)

For the co-located condition, which is thought to be more cognitively demanding, concussion group performance declined in the last half of the test while the control group performance steadily improved (Figure 2; Co-located, Group × Trial IXN: $F(9,29) = 2.35$, $p = 0.039$). In contrast, for the spatially separated conditions (i.e. noise in left or right ear only), performance over time steadily improved for both groups (Right, Group × Trial IXN: $F(9,29) = 1.03$, $p = 0.44$; Left, Group × Trial IXN: $F(9,29) = 1.16$, $p = 0.35$).

Children with concussion perform below norms on HINT

Across listening conditions, a greater proportion of the patients with concussions performed ≤50th percentile compared to controls (Figure 3), with the difference being more pronounced for the spatially separated conditions compared to the co-located condition (100% (20/20) vs. 65% (11/20) compared to 70% (14/20) vs. 35% (7/20)).

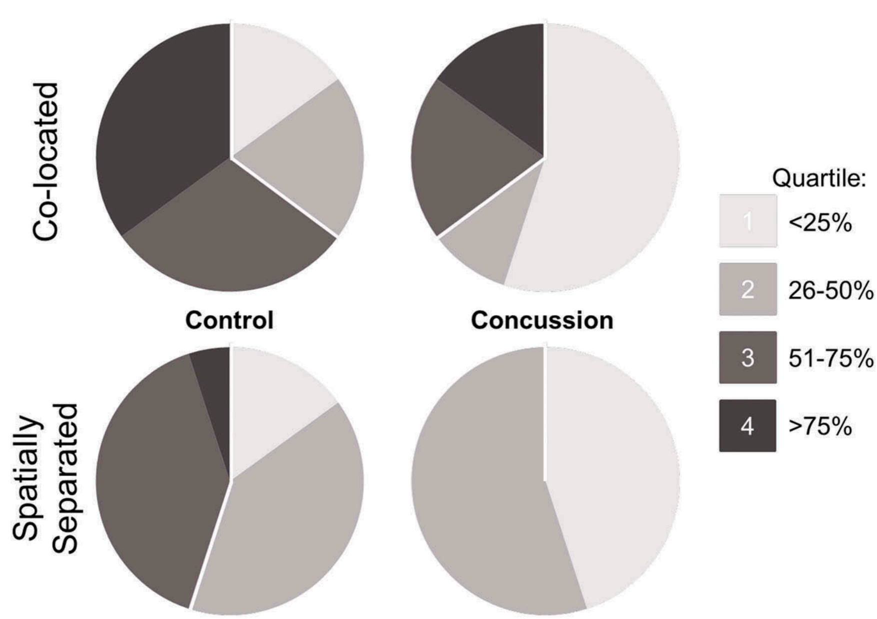

Figure 3. Age-group normative performance for the HINT for concussion and control groups. 'Co-located' refers to the listening condition in which speech and noise are presented together in space, while 'spatially separated' refers to an average of the conditions in which speech and noise are separated in space. The white line delineates the 50th percentile.

Discussion

This investigation is the first to show that children with concussions demonstrate poorer hearing-in-noise abilities compared to controls with no prior history of concussion. In addition to worse performance across listening conditions, children with concussions exhibited within-test performance fatigue: in the second half of the most demanding listening condition, concussion group performance declined across trials, while for controls, performance steadily improved. Taken together, these findings suggest that functional listening, such as the ability to understand speech in noise and the ability to sustain this skill over time in taxing listening conditions, may be compromised in children with concussions.

We previously published evidence of an auditory processing deficit following a concussion in children (13). Apart from this finding, however, investigations into concussion-related auditory impairments are limited, especially in youth. Anecdotal evidence of auditory-related complaints, such as difficulty listening in background noise, remembering and following oral instructions, and understanding rapid or degraded speech, have been reported in children with TBI (17), and accumulating evidence reveals auditory processing is impaired following a concussion in adults (8,9,11,12,14,28,29). The present findings provide the first evidence that there are functional consequences of auditory processing impairments in youth with concussions, and support the consideration of auditory function in the acute and long-term evaluation and management of concussion injuries.

The ability to hear in noisy environments is vital for everyday communication. For children and adolescents, this skill is especially important because academic environments are distracting (5) and noisy (6). As a result, competency in processing auditory stimuli is required to precisely encode a target signal (e.g. a teacher's voice) and filter out the noise (e.g. the chattering of classmates or rustling of papers). Cognitive skills, such as executive function (30), attention (31), and working memory (32), are drawn upon in the classroom, and are also recruited to attend to a signal and inhibit noise (33). Through integrating auditory and cognitive processes, the obstacle of speech-in-noise perception in the classroom can be overcome; if those processes are impaired following a concussion, this might add to the long list of challenges a child faces when returning to learn.

Perceiving speech in noise is not limited to the classroom, however. Athletic facilities, such as gymnasiums, arenas, and fields, can be noisy as well. In sports, this ability is not only engaged to identify a teammate's call, or to tune out the hum of the crowd, it is a communication skill used to play safely. Difficulty hearing in noise following a concussion might increase the already heightened risk of re-injury if a child is returned to sports too early, and should therefore be a factor to consider in return-to-play *and* return-to-learn decisions.

Finally, these results suggest that the HINT may provide a measure of auditory-cognitive endurance deficits in children with concussions. Performance trajectories in the more difficult, co-located listening condition show the concussion group fatiguing over time, reaching their peak threshold early on in contrast to control performance which improved steadily over time. Similar trial-by-trial performance trajectories that reflect performance 'trailing off' are evident in individuals with deficient sustained attention, such as children with attention-deficit-hyperactivity disorder (34,35). Many patients with concussion subjectively report deficits in cognitive endurance, in that they can perform a cognitive task well and without symptoms, but after a certain period of time they start to have difficulty with the task, feel fatigued, or experience other concussion symptoms (e.g. headache, dizziness). While current neuropsychological tests can measure many aspects of cognitive function, they are unable to objectively measure cognitive endurance. Our results suggest that HINT may be able to provide an objective measure of auditory-cognitive endurance, and thus help to guide academic accommodations for children with concussions, for example, as they relate to test-taking, especially standardized tests such as college entrance examinations.

Limitations and future directions

This study has some limitations. First is the sample size, which is modest, yet relatively large for case-control studies investigating auditory processing (8). Nonetheless, future investigations should test this research question in larger samples. Second, the time since injury for the concussion group is variable across patients, so it is unknown when these deficits are first evident and/or when they peak during the recovery process. Likewise, this is a cross-sectional, not longitudinal, sample, so it is still unknown how hearing-in-noise performance changes as children recover from their concussion injury.

Risk factors for prolonged recovery following a concussion include history of multiple head injuries (36), mental health problems (37), particularly depression (38), and family stressors (39), among others. Children with developmental and learning disorders, such as attention deficit hyperactivity disorder (ADHD), have a greater lifetime history of concussion (40), and perform poorly on speech-in-noise perception tasks (41–43). Given the overlapping challenge of careful listening between these disorders (44), and their shared co-morbidity in cases where concussion symptoms persist, it may be the case that the poor performance of the concussion group can be explained by confounding variables, rather than concussive effects. While plausible, only five participants of the concussion group reported learning disabilities, four of whom also reported history of anxiety. In addition, a systematic review of the concussion literature suggests children with learning disabilities or ADHD are not at a greater risk for developing post-concussion syndrome (45). It is therefore unlikely in this data set that confounding factors are driving the result; nonetheless, a follow-up investigation is needed to tease out the contributions of language and learning disorders to poor speech-in-noise perception.

Finally, future studies should evaluate how auditory processing and cognitive difficulties associated with concussions might impact academic performance, and whether specific rehabilitation protocols may be helpful in re-training hearing in noise such that children may recover these skills faster and thus return to classroom and sports sooner.

Conclusion

For the first time, we show evidence that children with a concussion demonstrate an impaired ability to understand speech in noisy backgrounds, as well as impaired ability to sustain this skill over time in taxing listening conditions. Both of these skills are essential for learning in a noisy, chaotic classroom and for executing sports-specific skills and plays in a loud gymnasium or outdoor sports setting. Thus, evaluating auditory processing may be helpful in a clinical setting to determine whether a child has fully recovered from a concussion and can therefore return to learning without accommodations and return to sport without an elevated risk for re-injury. Further research is warranted to investigate whether auditory processing rehabilitation programmes may facilitate recovery for children with concussions.

Acknowledgements

Many thanks to the members of the Auditory Neuroscience Laboratory for their thoughtful feedback on the manuscript, to the members of the Sports Medicine Research Group for their assistance with recruitment, and to the patients and their families for participating in the study. This work is supported by the Knowles Hearing Center at Northwestern University.

Declaration of interest

The authors report no conflicts of interest.

References

1. Jager TE, Weiss HB, Coben JH, Pepe PE. Traumatic brain injuries evaluated in U.S. emergency departments, 1992-1994. Academic Emergency Medicine. Off J Soc Acad Emerg Med. 2000;7(2):134–40. doi:10.1111/acem.2000.7.issue-2.
2. Koepsell TD, Rivara FP, Vavilala MS, Wang J, Temkin N, Jaffe KM, Durbin DR. Incidence and descriptive epidemiologic features of traumatic brain injury in King County, Washington. Pediatr. 2011;128(5):946–54. doi:10.1542/peds.2010-2259.
3. Binder LM. A review of mild head trauma. Part II: Clinical implications. J Clin Exp Neuropsychol. 1997;19(3):432–57. doi:10.1080/01688639708403871.
4. Ransom DM, Vaughan CG, Pratson L, Sady MD, McGill CA, Gioia GA. Academic effects of concussion in children and adolescents. Pediatr. 2015;135(6):1043–50. doi:10.1542/peds.2014-3434.
5. Shield BM, Dockrell JE. The effects of environmental and classroom noise on the academic attainments of primary school children. J Acoust Soc Am. 2008;123(1):133. doi:10.1121/1.2812596.
6. Sato H, Bradley JS. Evaluation of acoustical conditions for speech communication in working elementary school classrooms. J Acoust Soc Am. 2008;123(4):2064–77. doi:10.1121/1.2839283.
7. Vander Werff KR, Rieger B. Brainstem evoked potential indices of subcortical auditory processing after mild traumatic brain injury. Ear Hear. 2017 Mar;1. doi:10.1097/AUD.0000000000000411.
8. Turgeon C, Champoux F, Lepore F, Leclerc S, Ellemberg D. Auditory processing after sport-related concussions. Ear Hear. 2011;32(5):667–70. doi:10.1097/AUD.0b013e31821209d6.
9. Bergemalm P-O, Lyxell B. Appearances are deceptive? Long-term cognitive and central auditory sequelae from closed head injury. Int J Audiol. 2005;44(1):39–49. doi:10.1080/14992020400022546.
10. Saunders GH, Frederick MT, Arnold M, Silverman S, Chisolm TH, Myers P. Auditory difficulties in blast-exposed Veterans with clinically normal hearing. J Rehabil Res Dev. 2015;52(3):343–60. doi:10.1682/JRRD.2014.11.0275.
11. Gallun FJ, Papesh MA, Lewis MS. Hearing complaints among veterans following traumatic brain injury. Brain Inj. 2017;31(9):1183–87. doi:10.1080/02699052.2016.1274781.
12. Cockrell JL, Gregory SA. Audiological deficits in brain-injured children and adolescents. Brain Inj. 1992;6(3):261–66. doi:10.3109/02699059209029667.
13. Kraus N, Thompson EC, Krizman J, Cook K, White-Schwoch T, LaBella CR. Auditory biological marker of concussion in children. Sci Rep. 2016;6:39009. doi:10.1038/srep39009.
14. Kraus N, Lindley T, Colegrove D, Krizman J, Otto-Meyer S, Thompson EC, White-Schwoch T. The neural legacy of a single concussion. Neurosci Lett. 2017;646:21–23. doi:10.1016/j.neulet.2017.03.008.
15. Master CL, Scheiman M, Gallaway M, Goodman A, Robinson RL, Master SR, Grady MF. Vision diagnoses are common after concussion in adolescents. Clin Pediatr. 2016;55(3):260–67. doi:10.1177/0009922815594367.
16. Alsalaheen BA, Mucha A, Morris LO, Whitney SL, Furman JM, Camiolo-Reddy CE, Collins MW, Lovell MR, Sparto PJ. Vestibular rehabilitation for dizziness and balance disorders after concussion. J Neurol Phys Ther. 2010;34(2):87–93. doi:10.1097/NPT.0b013e3181dde568.
17. Lew HL, Thomander D, Chew KTL, Bleiberg J. Review of sports-related concussion: potential for application in military settings. J Rehabil Res Dev. 2007;44(7):963–74. doi:10.1682/JRRD.2006.12.0169.
18. Gallun FJ, Diedesch AC, Kubli LR, Walden TC, Folmer RL, Lewis MS, McDermott DJ, Fausti SA, Leek MR. Performance on tests of central auditory processing by individuals exposed to high-intensity blasts. J Rehabil Res Dev. 2012;49(7):1005–25. doi:10.1682/JRRD.2012.03.0038.
19. Hoover EC, Souza PE, Gallun FJ. Auditory and cognitive factors associated with speech-in-noise complaints following mild traumatic brain injury. J Am Acad Audiol. 2017;28(4):325–39. doi:10.3766/jaaa.16051.
20. Halstead ME, McAvoy K, Devore CD, Carl R, Lee M, Logan K. Council on Sports Medicine and Fitness, Council on School Health. Returning to learning following a concussion. Pediatr. 2013;132(5):948–57. doi:10.1542/peds.2013-2867.
21. Centers for Disease Control and Prevention (CDC). CDC grand rounds: reducing severe traumatic brain injury in the United States. MMWR Morb Mortal Wkly Rep. 2013;62(27):549–52.
22. McCrory P, Meeuwisse WH, Aubry M, Cantu B, Dvořák J, Echemendia RJ, Engebretsen L, Johnston K, Kutcher JS, Raftery M, et al. Consensus statement on concussion in sport: the 4th international conference on concussion in sport held in Zurich, November 2012. Br J Sports Med. 2013;47(5):250–58. doi:10.1136/bjsports-2013-092313.
23. Lovell MR, Iverson GL, Collins MW, Podell K, Johnston KM, Pardini D, Pardini J, Norwig J, Maroon JC. Measurement of symptoms following sports-related concussion: reliability and normative data for the post-concussion scale. Appl Neuropsychol. 2006;13(3):166–74. doi:10.1207/s15324826an1303_4.
24. U.S. Census Bureau. 2011-2015 American Community Survey 5-year estimates. Available from 2015. https://www.census.gov/acs/www/data/data-tables-and-tools/dataprofiles/2015/.
25. Nilsson M, Soli SD, Sullivan JA. Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. J Acoust Soc Am. 1994;95(2):1085–99. doi:10.1121/1.408469.
26. Bench J, Kowal A, Bamford J. The BKB (Bamford-Kowal-Bench) sentence lists for partially-hearing children. Br J Audiol. 1979;13(3):108–12. doi:10.3109/03005367909078884.
27. Soli SD, Wong LLN. Assessment of speech intelligibility in noise with the Hearing in Noise Test. Int J Audiol. 2008;47(6):356–61. doi:10.1080/14992020801895136.
28. Vander Werff KR, Rieger B. Brainstem evoked potential indices of subcortical auditory processing after mild traumatic brain injury. Ear Hear. 2017;38(4):e200–e214. doi:10.1097/AUD.0000000000000411.

29. Kraus N, Thompson EC, Krizman J, Cook K, White-Schwoch T, LaBella CR. Auditory biological marker of concussion in children. Sci Rep. 2016 [accessed 2018 Feb 17];6(1). http://www.nature.com/articles/srep39009. doi:10.1038/srep39009.
30. Meltzer L. Promoting executive function in the classroom. New York: Guilford Press; 2010.
31. Piontkowski D, Calfee R. Attention in the classroom. In: Hale GA, Lewis M, editors. Attention and cognitive development. Boston, MA: Springer US; 1979. p. 297–329. http://link.springer.com/10.1007/978-1-4613-2985-5_11. doi:10.1007/978-1-4613-2985-5_11.
32. Gathercole SJ, Lamont E, Alloway TP. Working memory in the classroom. In: Working memory and education. Amsterdam; Boston, Mass: Academic Press; 2006. p. 219–40. (Educational psychology series).
33. Allen P, Wightman F. Effects of signal and masker uncertainty on children's detection. J Speech Hear Res. 1995;38(2):503–11. doi:10.1044/jshr.3802.503.
34. Barry JG, Ferguson MA, Moore DR. Making sense of listening: the IMAP test battery. J Visualized Exp. 2010 [accessed 2016 Apr 21];(44). http://www.jove.com/index/Details.stp?ID=2139. doi:10.3791/2139.
35. Moore DR, Ferguson MA, Edmondson-Jones AM, Ratib S, Riley A. Nature of auditory processing disorder in children. Pediatrics. 2010;126(2):e382–e390. doi:10.1542/peds.2009-2826.
36. Abrahams S, Fie SM, Patricios J, Posthumus M, September AV. Risk factors for sports concussion: an evidence-based systematic review. Br J Sports Med. 2014;48(2):91–97. doi:10.1136/bjsports-2013-092734.
37. Morgan CD, Zuckerman SL, Lee YM, King L, Beaird S, Sills AK, Solomon GS. Predictors of postconcussion syndrome after sports-related concussion in young athletes: a matched case-control study. J Neurosurg Pediatr. 2015;15(6):589–98. doi:10.3171/2014.10.PEDS14356.
38. Zemek R, Barrowman N, Freedman SB, Gravel J, Gagnon I, McGahern C, Aglipay M, Sangha G, Boutis K, Beer D, et al. Clinical risk score for persistent postconcussion symptoms among children with acute concussion in the ED. Jama. 2016;315(10):1014. doi:10.1001/jama.2016.1203.
39. Ponsford J, Willmott C, Rothwell A, Cameron P, Ayton G, Nelms R, Curran C, Ng KT. Cognitive and behavioral outcome following mild traumatic head injury in children. J Head Trauma Rehabil. 1999;14(4):360–72. doi:10.1097/00001199-199908000-00005.
40. Iverson GL, Wojtowicz M, Brooks BL, Maxwell BA, Atkins JE, Zafonte R, Berkner PD. High school athletes with ADHD and learning difficulties have a greater lifetime concussion history. J Atten Disord. 2016 Jul 18 [accessed 2017 Jul 22]. http://jad.sagepub.com/cgi/doi/10.1177/1087054716657410. doi:10.1177/1087054716657410.
41. Boets B, Vandermosten M, Poelmans H, Luts H, Wouters J, Ghesquière P. Preschool impairments in auditory processing and speech perception uniquely predict future reading problems. Res Dev Disabil. 2011;32(2):560–70. doi:10.1016/j.ridd.2010.12.020.
42. Bradlow AR, Kraus N, Hayes E. Speaking clearly for children with learning disabilities: sentence perception in noise. J Speech, Language, and Hearing Res. 2003;46(1):80–97. doi:10.1044/1092-4388(2003/007).
43. Davis MH, Johnsrude IS. Hearing speech sounds: top-down influences on the interface between audition and speech perception. Hear Res. 2007;229(1–2):132–47. doi:10.1016/j.heares.2007.01.014.
44. Sharma M, Purdy SC, Kelly AS. Comorbidity of auditory processing, language, and reading disorders. J Speech, Language, and Hearing Res. 2009;52(3):706–22. doi:10.1044/1092-4388(2008/07-0226).
45. Iverson GL, Gardner AJ, Terry DP, Ponsford JL, Sills AK, Broshek DK, Solomon GS. Predictors of clinical recovery from concussion: a systematic review. Br J Sports Med. 2017;51(12):941. doi:10.1136/bjsports-2017-097729.