USING THE HEARING-IN-NOISE TEST AS A SCREENING TOOL FOR COCHLEAR SYNAPTOPATHY IN STUDENT MUSICIANS

by

Stéphanie Monette

B.Sc., University of Ottawa, 2016

M.A., University of Ottawa, 2017

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Audiology and Speech Sciences)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

December 2020

The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, the thesis entitled:

Using the hearing-in-noise test as a screening tool for cochlear synaptopathy in student musicians

submitted by Stéphanie Monette in partial fulfillment of the requirements for

the degree of Master of Science

in Audiology and Speech Sciences

Examining Committee:

Dr. Valter Ciocca, Professor, School of Audiology and Speech Sciences, UBC
Supervisor

Dr. Sigfrid Soli, Adjunct Professor, School of Audiology and Speech Sciences, UBC
Supervisory Committee Member

Dr. Navid Shahnaz, Associate Professor, School of Audiology and Speech Sciences, UBC
Supervisory Committee Member

Abstract

Objective: Recent studies in rodents show that noise exposure may cause permanent damage to inner hair cell synapses, even when hearing thresholds return to their baseline (Fernandez et al., 2015; Liberman et al., 2015). Emerging evidence indicates that similar damage may occur in humans (Liberman et al., 2016), and is known in the literature as cochlear synaptopathy (CS) or hidden hearing loss. CS would likely cause functional deficits in temporal coding and speech-in-noise (Furman, Kujawa & Liberman, 2013; Kumar et al., 2012). The objective of the current research was to compare the speech-in-noise performance of an at-risk group of student musicians to a control group of individuals with limited noise exposure.

Method: The experimental group consisted of 20 student musicians (M_{AGE} = 22.7, SD = 3, range =18-28). The control group was comprised of 22 students with normal hearing and limited noise exposure (M_{AGE} = 21.9, SD = 2.5, range =18-27). Previous noise exposure was estimated using the Noise Exposure Structured Interview (NESI; Guest et al., 2018). The hearing-in-noise test (HINT; Nillson et al., 1994) and the random gap-in-noise test (RGDT; Keith, 2000) were administered to assess temporal and speech-in-noise perception abilities. A Bayesian multilevel linear model was used to investigate differences in HINT scores between groups and conditions.

Results: The musician group showed higher estimated lifetime exposure than the control group. Differences were found between conditions of the HINT, but not between groups. No association was found between HINT-ITD and estimated lifetime noise exposure.

Discussion: It is possible that the population studied did not have sufficient noise exposure to exhibit difficulties processing temporal stimuli. Given the current literature on CS in humans, strict inclusion criteria, broad research protocols and interdisciplinary collaborations are

warranted. Future studies should focus on finding behavioral tests with good sensitivity and specificity to reliably diagnose CS in humans in older musicians.

Lay Summary

Recent studies in rodents show that noise exposure may cause permanent damage to inner hair cell synapses (Fernandez et al., 2015; Liberman et al., 2015). This damage, known in the literature as hidden hearing loss or cochlear synaptopathy, may also occur in humans (Liberman et al., 2016). Loss of these synapses may lead to functional deficits in the use of temporal elements of sound and in speech-in-noise performance. The current study compares the performance of young musicians and a control group of non-musicians on the hearing-in-noise test and the random gap in noise test. Findings of the current study do not demonstrate a difference in speech-in-noise perception between groups.

Preface

This research project is part of a larger project on cochlear synaptopathy taking place in the Middle Ear Laboratory at the University of British Columbia under the coordination of Dr. Navid Shahnaz. The research project was approved by the University of British Columbia Research Ethics Board (certificate number #H16-02052) under the title "Hidden Hearing Loss – HHL".

Data collection for the project was conducted by Ainsley Ma, Charlene Chang, Natalie Tran and myself. The full protocol consisted of three different testing sessions. I administered tests that are a part of the second session of the protocol, which included the temporal modulation transfer function test, the triplet digit test, the hearing-in-noise test and the random gap in noise test. Occasionally, data collection for session 2 was conducted by Charlene Chang or Ainsley Ma, and I occasionally participated in data collection for session 1 of the project (see Appendix A for a description of the full project protocol). University of British Columbia Audiology students (Elizabeth Dunlop, Haley Gynane, Mitchel Harris, Shandryn Kozin, Danielle Lafleur, Kelsey Miller, Darren Roussel, Saruka Santhiran, Natalie Tran, Jaclyn Wiebe) also participated in data collection for the first and second sessions of 4 musicians and 3 non-musician participants, as part of a Research Methods class.

Pilot testing specifically for the hearing-in-noise test was carried out from September to December 2019 by myself. Protocol implementation consisted of a collaboration between Dr. Sig Soli, Dr. Valter Ciocca and myself. The data analysis was a collaboration between Dr. Valter Ciocca and myself.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ANF – Auditory nerve fiber

ANSI – American national standard institute

ABR – Auditory brainstem response

CS – Cochlear synaptopathy

DPOAE – Distortion product otoacoustic emission

EHF – Extended high frequency

HINT – Hearing-in-noise test

ILD – Interaural level difference

ITD – Interaural time difference

KEMAR - Knowles Electronics Manikin for Acoustic Research

LENS-Q – Lifetime exposure of noise and solvents questionnaires

LiSN-S – Listening in spatialized noise – sentences

NEQ – Noise exposure questionnaire

NESI – Noise exposure structured interview

NF – Noise front

NS – Noise side

OHC – Outer hair cell

RGDT – Random gap detection test

SIN – Speech-in-noise

SR – Spontaneous rate

SNR – Signal-to-noise ratio

Acknowledgements

I offer my gratitude to the faculty, staff and fellow students at the University of British Columbia, who have inspired me to continue my work in this field. I owe particular thanks to my supervisor Dr. Valter Ciocca for guidance and generosity with his time. I would also like to thank Dr. Sigfrid Soli for his expertise. I thank Dr. Navid Shahnaz for access to an engaging research team and laboratory space. Special thanks are owed to Charlene Chang, Ainsley Ma and Natalie Tran for the coordination of testing and collaboration on the implementation of this project. Thank you to my thesis committee, Dr. Valter Ciocca, Dr. Navid Shahnaz and Dr. Sig Soli for their support and Dr. Robert Prichart for the circulation of study postings to University of British Columbia music students.

This research was funded through a Canada Graduate Scholarship – Masters Canadian Institutes of Health Research scholarship.

Special thanks are owed to my parents and partner, who have encouraged me throughout my years of education.

Dedication

To my family.

Chapter 1: Introduction

Maximum permitted noise exposure levels for Canadian workers differ depending on jurisdiction (Canadian Centre for Occupational Health and Safety, 2016). These noise regulations are based on the assumption that temporary hearing threshold shifts do not result in permanent damage to the hair cells (Arenas & Sulter, 2014). However, studies using animal models show that permanent damage may occur to auditory structures even if hearing thresholds go back to their baseline (e.g. Robertson, 1983; Liberman, 1982; Spoendlin, 1971). This type of damage perturbs the transmission of information between the inner hair cells and auditory nerve fibers (ANF) and has been designated in the literature as "cochlear synaptopathy" (CS) or "hidden hearing loss" (Schaette & McAlpine, 2011).

1.1 Cochlear Synaptopathy

Studies on animal models demonstrate that synapses between inner hair cells and ANFs may be the most vulnerable structure to noise-induced damage (Furman et al., 2013; Kujawa & Liberman, 2009; Lin et al., 2011). There are two types of ANFs that connect hair cells in the organ of Corti to higher levels of processing. Type I ANFs synapse with inner hair cells whereas type II connects with outer hair cells (Fuchs et al., 2003). Type I ANFs can be further divided into categories based on spontaneous rate (SR) of firing and amount of depolarization needed to generate an action potential. Approximatively 60% of all type I ANFs have a high-SR and low thresholds (Liberman et al., 2011). Structurally, these fibers have thicker axons and more mitochondria in their peripheral terminals (Liberman, 1988; Liberman & Kiang, 1978; Liberman et al., 2011). Noise-induced CS seems to be selective to ANFs with a high threshold and low-SR that connect to inner hair cells (Furman et al., 2013; Liberman & Liberman, 2015). Several authors suggest that the vulnerability of low-SR ANFs to noise may be due to glutamate exotoxicity (Liberman & Kujawa, 2017; Liberman, 1982; Robertson, 1983; Spoendlin, 1971). Glutamate can have toxic properties in the nervous system when it is released in excess, resulting in swelling as calcium and water enter the neuron (Mayer & Westbrook, 1987). Low-SR ANFs have a lower capacity of glutamate reuptake compared to high-SR ANFs, as demonstrated in an immunostaining study (Furness et al., 2003). When low-SR ANFs are damaged, hearing thresholds remain unaffected because high-SR fibers are still able to respond to low-level sounds (Furman et al., 2013). CS due to noise overexposure has been demonstrated in noise-exposed mice (Kujawa & Liberman, 2009), rats (Lobarinas et al., 2017), guinea pigs (Furman et al., 2013; Lin et al., 2011), chinchillas and rhesus macaques (Hickox et al., 2017; Valero, Burton et al., 2017). Studies on CS in mice models show a rapid loss of peripheral terminals of the inner hair cell ANFs, followed by a slow cell death and disappearance of nerve fibers after a period that can vary from months to years (Kujawa and Liberman, 2009; Liberman et al., 2015). However, the picture for humans is less straightforward than in other animals.

1.2 Cochlear Synaptopathy in Humans

Makary et al. (2011) conducted histological post-mortem analyses on 100 human cochleae with no significant hair-cell loss. Makary and colleagues counted individual ANFs and were able to conduct cross-comparisons with different age groups. A steady decline of mean ANFs was observed as age increased. By the age of 90 years old, a mean loss of 30% of ANFs was found. Furthermore, cases with clear noise-exposure history had individual ANF counts well below the mean obtained for those with no clear history of noise exposure. Makary et al.'s results provide suggestive evidence of a loss of ANFs through life events such as excessive noise exposure and aging. Because such invasive methods are not possible during an individual's lifetime, researchers have turned to non-invasive electrophysiological and behavioral methods to find sensitive measures of CS in humans.

In rodent models, wave I amplitude of the auditory brainstem response (ABR), produced by synchronous firing of ANFs (Hashimoto et al., 1981), has been found to diagnose CS accurately (Kujawa and Liberman, 2009; Sergeyenko et al., 2013 Mehraei et al., 2016; Fernandez et al., 2015; Valderrama et al., 2018). In humans, some studies have noted altered ABRs in individuals with a history of noise exposure and normal audiograms (e.g. Valderrama et al., 2018; Bramhall et al., 2017; Stamper and Johnson, 2015). However, other groups have not reported such a relationship (e.g. Prendergast et al., 2017; Kluk, Prendergast, Guest, Munro & Léger, 2016). Other electrophysiological measures that have been used to investigate CS include forward masking ABR (e.g. Mehraei et al., 2017), electrocochleography (e.g. Liberman et al., 2016; Stuermer et al., 2015), frequency following response (e.g. Prendergast et al., 2017) and envelope following response (e.g. Guest et al., 2017). Again, there have been mixed results for these measures, where some studies report worse results for individuals at-risk of CS (Liberman et al., 2016; Stuermer et al., 2015), whereas others do not (e.g. Guest et al., 2017; Mehraei et al., 2017; Prendergast et al., 2017). Amplitudes and latencies of individual ABR waves vary considerably in humans (Trune et al., 1988). These variations are attributable to many factors such as head size, sex and physiological noise (Plack et al., 2016), which could explain why results have been mixed. In many of these electrophysiological studies, electrode placement or impedance across trials can be a source of interference (Plack et al., 2016). An additional limitation of physiological measures is that they are not always feasible in clinical settings due to time and financial constraints.

To date, there is no single test that allows for a reliable diagnosis of CS in humans. As the field is still in its early days, some researchers have chosen a test-battery approach, allowing an investigation of most aspects of auditory function in relation to CS (e.g. Liberman et al., 2016; Verhulst et al., 2018). The current study is part of a larger project investigating a variety of behavioral and electrophysiological measures in listeners at risk of CS. In the context of this dissertation, the review will focus on the use of questionnaires about noise exposure measurements, extended-high frequency audiometry, supra-threshold measures of temporal processing, and speech-in-noise (SIN) tasks.

1.2.1 Noise exposure questionnaires

In animal models, researchers can decide on precise decibel (dB) levels and timeframes of noise exposure that are just enough to cause CS with little or no hair cell damage. Noise exposure in humans is less easily controlled and difficult to measure accurately throughout the lifetime. Often, guided self-reports are conducted through questionnaires or interviews. Recently, three measures of noise exposure have been used in CS studies: the Noise Exposure Questionnaire (NEQ – Johnson et al., 2017; Bernard et al., 2019), the Lifetime Exposure of Noise and Solvents Questionnaires (LENS-Q; Bramhall et al., 2017; Griest et al., 2015; Gordon et al., 2017) and the Noise Exposure Structured Interview (NESI; Guest et al., 2018). The NEQ (Bernard et al., 2019) was created to quantify an individual's annual occupational and recreational noise exposure. In this questionnaire, participants are asked to report time spent in noisy settings. While it gathers important information on noisy activities, the NEQ does not account for the use of hearing protection. The LENS-Q consists of an in-depth questionnaire about frequency and duration of exposure, as well as use of hearing protection for a variety of possible sources of noise exposure, such as nonmilitary occupational noise, military occupational noise and recreational noise. The reliability and validity of the both the NEQ and the LENS-Q has not been assessed. The NESI consists of a standardized interview script that is structured, yet flexible depending on the individuals' previous noise exposure (Guest et al., 2018). In other words, it is able to account for changing exposure habits over the lifetime by dividing the lifespan into periods. The experimenter requests information on all noisy activities and asks participants to use a vocal effort chart to determine an approximate sound level for each activity. Using information from exposure duration, sound level and use of hearing protection for each activity, an estimation of lifetime noise exposure is calculated in units of noise exposure, where one unit is equivalent to one year of work at 90 dBA. Dewey et al. (2018) tested 19 music-industry workers and 43 non-music industry workers on the NESI (age range = 25 – 40). Music industry workers obtained values in the upper end of the overall range (between ~4 and 300) and had a high density of scores centered around 20 units of noise exposure. By contrast, the NESI scores for the non-music group were less spread out (between ~0.01 and 100). The NESI has also been used in studies on CS (Guest et al., 2017; Shehorn et al., 2020). Guest and colleagues matched a group of 16 individuals (range = 18-40 years of age) with impaired speech perception in noise (SIN) with 16 control participants on the basis of age, sex and audiometric thresholds up to 14 kHz. They found that units of lifetime noise exposure obtained were similar for individuals with SIN impairments ($M_{NESI} \approx 9.5$, range ≈ 0.7 - 55) and control listeners ($M_{NESI} \approx 7.5$, range ≈ 0.2 - 95). Reliability of the NESI was evaluated by comparing reported dB level based on vocal effort and noise levels directly measured in workplace settings using a dosimeter (Ferguson et al., 2019). In this comparative study, Ferguson and colleagues tested 168 young adults between 16-25 years of age. Of the 168 young adults who participated in the study, 91% reported noise levels within 6 dB of the direct measurement and 56% reported levels within 3 dB of the direct noise measurements from their workplace. On the basis of this evidence, using vocal effort as method to estimate noise levels likely has good reliability, allowing for a decent estimation of lifetime noise exposure through the NESI.

1.2.2 Measures of temporal processing

As noted previously, CS likely affects primarily type I ANFs that have a low-SR and high thresholds. Damage to these fibers could cause a desynchronization in ANF firing, affecting the temporal coding of sounds (Bharadwaj et al., 2014; Lopez-Poveda & Barrios, 2013). Thus, researchers have turned to assessments of temporal acuity to investigate functional consequences of CS, such as interaural time difference (ITD) detection thresholds. One assessment of temporal processing that has not been used previously in CS studies is gap detection.

1.2.2.1 Gap detection

Gap detection has been integrated into test batteries for central auditory processing disorders in children and adults as a way to evaluate temporal resolution (e.g. Dias et al., 2011). In this forced choice task, two stimuli are presented with intervening silent intervals (i.e. gaps) of varying duration. Listeners are asked to indicate when they detect the presence of one long or two short sounds. Although pure tones, clicks, and bursts of broadband noise have been used in gap detection studies, broadband noise has the advantage of masking spectral splatter caused by abruptly terminating a sound (Jerger and Musiek, 2000; Trehub et al., 1995). There are two commercially available gap detection tests that allow the use of broadband noise stimuli: the gaps-in-noise test (GIN; Musiek et al., 2005) and the random gap detection test (RGDT; Keith, 2000), which both have good specificity and reliability (Musiek et al., 2005). In the GIN test, a series of 6-sec segments of broadband noise containing 0 to 3 silent gaps are presented. The stimulus intervals can vary between 2, 3, 4, 6, 8, 10, 12 ,15 and 20 msec. In this test, the gap duration and location of gaps within the noise segments are pseudorandomized (Musiek et al., 2005). In the RGDT, the gap location is always in the middle and typically varies between 0, 2, 4, 8, 10, 15, 20 msec. The segments can be presented either randomly or through an adaptive procedure. Previous studies using broadband noise stimuli with these two methods found gap detection thresholds between 2 and 4.9 msec for young adults with normal hearing (Lister, Roberts & Lister, 2011; Musiek et al., 2005). The current study evaluates temporal resolution using the RGDT because there is evidence that it is more strongly associated with SIN performance than the GIN (Hoover, Pasquesi, and Souza, 2015).

1.2.2.2 Interaural time differences

One temporal processing cue that could be affected by CS is the "interaural time difference" (ITDs). ITDs result from the difference in the physical distance between a sound source and each ear (Plack, 2014, p.158). Low-frequency neurons are likely responsible for the encoding of this binaural cue (Middlebrooks and Green, 1990; Wightman, Kisler and Anderson, 1992). ITDs become ambiguous above about 750 Hz because the half-wavelength at this frequency is shorter than the distance between the two ears of an average head. Two studies have used ITD detection thresholds (i.e., the smallest detectable ITD) to explore the functional consequences of CS (Bharadwaj et al., 2015; Mehraei et al., 2016). Bharadwaj et al. (2015) used a series of suprathreshold auditory tests to investigate functional consequences of CS in participants with low and high noise exposure. Participants were placed in low-exposure and high-exposure groups based on their answers on a questionnaire looking at the frequency of reported attendance to loud events, the number of times they experienced temporary threshold shifts, and whether or not they use earphones on a regular basis. The high-exposure group had significantly higher ITD thresholds compared to the low-exposure group. However, results in

Bharadwaj et al. (2015) should be interpreted with caution due to the nature of their noise exposure measure, a short questionnaire, and the small sample of participants. Mehraei and colleagues investigated normal hearing listeners' sensitivity to ITDs in relation to wave V latency shifts in noise. This ABR measure is thought to be an indicator of the integrity of low-SR fibers, as these fibers have a delayed onset response relative to high-SR fibers (Bourien et al., 2014). Mehraei and colleagues found that wave V latency-shift in noise predicted the envelope ITD thresholds, which ranged from ~200 to 800 µs. Listeners who showed large wave-V latency shifts with increasing noise performed better on ITD thresholds for both 2 kHz and 4 kHz. Together, evidence from Bharadwaj et al. (2015) and Mehraei et al. (2016) is consistent with the idea that ITDs may be encoded to some extent by low-SR ANFs and may be affected by noise exposure.

Spatial separation of target sound and background noise give us access to interaural level differences (ILDs), as well as ITD cues. ILD cues rely on the difference in sound level between the two ears as a consequence of the relative difference in the location of the ears relative to a given sound source (Plack, 2014, p. 162). Unlike ITDs, the difference in level between ears is a more effective localization cue at high-frequencies because high-frequency sounds are more easily attenuated by the head, creating a head-shadow effect. ITD and ILD cues not only help with sound localization but also in the detection of speech in background noise (Plack, 2014, p.162). For example, Culling et al. (2004) investigated the role of ITD and ILD cues in understanding speech in competing backgrounds. They found that listeners had more advantage due to spatial separation when both ILD and ITD cues are available, and that when speech was separated from the interfering signal by 90 degrees, listeners benefitted more from ITD than ILD cues. This first conclusion is in-line with the effect known as "spatial release from masking"

(Carhart et al., 1969; Shinn-Cunningham et al., 2001), where listeners achieve better SIN recognition when speech is separated from noise due to increased access to ITD and ILD cues. A number of other studies with normal hearing listeners show that ITD cues have greater contribution to on one's ability to perceive SIN than ILD cues (e.g. Glyde et al., 2013; Bernstein & Trahiotis, 2015, 2016). Using a SIN test that allows for independent manipulation of ITD and ILD cues would be of importance, as ITD perception could be disrupted to a greater extent in listeners with suspected CS.

1.2.3 Tests of speech perception in noise

Kujawa & Liberman (2009) suggested that the damage to Type I ANFs could be especially apparent in situations with low signal-to-noise ratios (SNR), such as during speech recognition in noise. Thus, some researchers have turned to SIN tests to evaluate functional consequences of CS. SIN ability is usually measured by establishing a speech reception threshold (SRT). The SRT is the SNR (S/N, measured in dB) at which a fixed percentage (usually 50%) of a speech material is recognized accurately (Plomp, 1976).

Some SIN tests frequently used in clinic or research settings include the Hearing-in-Noise test (HINT; Nilsson et al., 1994), the Listening in Noise - Sentences test (LiSN-S; Cameron, Dillon & Newal, 2006) and the Quick Speech-in-Noise test (QuickSIN; Killion et al., 2004). The table below summarizes the characteristics of each of these tests.

Table 1.1 Comparison of common speech-in-noise tests

	HINT (Nilsson et al., 1994)	QuickSIN (Killion et al., 2004)	LiSN-S (Cameron, Dillon & Newal, 2006)
Objective	Evaluations of binaural hearing aid fittings	Evaluation of difficulties in SIN perception and guide hearing aid selection for adults	Evaluation of auditory processing in children
Sentences	Simple sentences; Grade 1 reading level 12 lists of 20 sentences	Complex and semantically unpredictable 12 lists of 6 sentences	Simple sentences 120 sentences, up to 30 sentences per condition
Speaker	Male	Female	Female
Background noise	Speech-shaped noise at 0°, 90 or 270° azimuth	Multi-talker babble at 0° azimuth	Distractor story; same or different voices at 0°, +/-90° azimuth
Speech location	0° azimuth	0° azimuth	0° azimuth
Stimulus presentation level	Background noise remains fixed at 65 dB(A)	Sentences remain fixed at 80 dB HL	Distractor story remains fixed at 55 dB SPL
Step size	4 dB then 2 dB	5 dB	4 dB then 2 dB
Transducers	Loudspeaker, TDH earphones or HDA earphones	Loudspeaker, insert earphones or TDH earphones	HD215 headphones
Time of completion	5 minutes per list	1 minutes per list	5 minutes per list
Normative sample	67 adults (M_{AGE} = 38.7 years) with normal hearing using headphones *N.B. It is suggested to create own clinic norms if using soundfield.*	26 adults with normal hearing using insert earphones	132 adolescents and adults (range = 12 to 60 years of age) with normal hearing

Fundamentally, these tests differ in terms of type of background noise, speakers, utterance length and sentence complexity. Background sounds can have masking effects at the level of the periphery (e.g. neural representation) or at higher levels of processing. Overlapping neural signals can degrade the target speech, known as "energetic masking" in the literature (Kidd et al., 2008). At higher levels of processing, semantic information in the background noise can distract from the task at hand (Röer et al., 2017) and is known as "informational masking" (Kidd et al., 2008). QuickSIN and LiSN-S use distractor speech as the background signal, which allows both energetic and informational masking, whereas the HINT leads exclusively to energetic masking as speech-shaped noise is used. These different types of background noise have an impact on the amount of spatial release from masking obtained. For instance, in normal hearing listeners, a primarily informational masker led to an 18 dB spatial release from masking, whereas an energetic masker led to 7 dB spatial release from masking (Arbogast et al., 2002). Using speech as background noise could also introduce an unwanted source of variability to threshold measurements, due unpredictable access to dip listening during amplitude and spectral dips in the distractor speech signal (Freyman et al., 1999). QuickSIN includes sentences that are less semantically predictable and a more complex vocabulary than HINT (e.g. HINT: 'The wife helped her husband'; QuickSIN: 'A cruise in warm waters in a sleek yacht is fun') (Wilson et al., 2007). Additionally, HINT sentences are shorter (mean = 5.3 words) than QuickSIN sentences (mean = 8.3 words) (Parbery-Clark et al., 2009). All three tests have been widely used in clinical studies but only HINT and LiSN-S can be used to estimate the use of sound localization cues for speech perception, as QuickSIN does not spatially separate speech from noise signals. The current study will use HINT as the noise level of presentation is higher, and more similar to the noise in typical noisy environments, than the distractor level in LiSN-S. A higher level of presentation could lead to additional involvement of Type I ANFs with low-SR and high thresholds. In addition to the advantage of relying only on energetic masking, the experimental version of HINT used in the current study allowed for the independent manipulation of ITD and ILD cues, which was not available in LiSN-S.

1.2.3.1 Noise exposure and speech-in-noise perception

To date, a number of studies have found that higher noise exposure can lead to difficulties in SIN perception in individuals with occupational noise exposure such as train drivers (Kumar et al., 2012), shipyard workers and preschool teachers (Kujala et al., 2004), military workers (Alvord, 1983; Hope et al., 2013) or musicians (Liberman et al., 2016) (see Le Prell & Clavier, 2016 for a review). Notably, Liberman et al. (2016) investigated individuals at-risk of CS on a number of measures including SIN perception. Their study included 34 participants between the ages of 18 and 41 who were assigned into high-risk and low-risk groups based on their answers on a noise exposure questionnaire. Most of the participants in the high-risk group were music students from the local university. All participants had normal hearing at conventional frequencies (250-8000 Hz) and present distortion product otoacoustic emissions (DPOAE), indicating good outer hair cell function. Liberman and colleagues used electrocochleography to assess the integrity of ANFs. This measure allowed for a calculation of the SP/AP ratio: the ratio of summating potential generated by hair cells over the action potential generated by the cochlear nerve. Their test battery also included word recognition testing at 35 dB HL using the Northwestern University Auditory Test Number 6 (NU-6; Tillman and Carhart, 1966), a list of 50 phonetically balanced words. Word recognition scores were obtained under various conditions, including: (1) in quiet, (2) in the presence of ipsilateral noise at an SNR of 5 dB or 10 dB. While both groups performed similarly in word recognition in quiet, the high-risk group had more difficulty with word recognition in the noise conditions. The authors suggested that the performance differences may be due to CS as the SP/AP ratios correlated with performance in all conditions of word recognition in noise. However, Yeend et al. (2017) suggested that the difference in SIN performance between listeners with normal hearing and those with CS may also be due to the higher EHF thresholds obtained by the at-risk group. While some studies found a positive association between noise exposure and difficulties with SIN perception, the literature on this topic is not consistent. Researchers have subsequently reported either a failure to reject the null hypothesis (e.g. Fulbright et al., 2017; Grinn et al., 2017; Grose et al., 2017; Guest et al., 2018; Le Prell et al., 2018; Yeend et al., 2017). Another explanation for these inconsistencies could lie in the variations of lifetime noise exposure between experimental groups. For instance, participants in Fulbright et al. (2017) were assigned to the experimental and control groups based on the amount of recreational noise exposure, whereas those in Liberman et al. (2016) were classified into high-risk and low-risk group based on both recreational and occupational noise exposure. Most of the high-risk participants in the study by Liberman et al. (2016) were music students. The following section will discuss the speech in noise performance by musicians.

1.3 Musicians and speech-in-noise perception

Musicians are an interesting population to study in the context of CS, as they are often exposed to an amount of noise that exceeds recommended limits through their solo practice, small and large group practice and concerts (Chasin, 2009). Musicians are an at-risk population for hearing disorders such as sensorineural hearing loss, tinnitus or hyperacusis (Di Stadio et al., 2018). Yet, hearing protection is underused by both student and professional musicians (Laitinen, 2005; Zander et al., 2008). While intensive musical practice likely increases the risk of a hearing loss, music training has also been widely investigated as a form of experience-dependent neuroplasticity in the auditory system (Pantev & Herholz, 2011; Bidelman & Alain, 2015). Several researchers have suggested that musicians have enhanced encoding of sound at different steps of the auditory pathway, including the auditory cortex (Schneider et al., 2002; Bianchi et al., 2019; Du and Zatorre, 2017), brainstem (Musacchia et al., 2007, 2008; Wong et al., 2007; Parbery-Clark et al., 2009, 2011; Bidelman and Krishnan, 2010; Bidelman et al., 2011) and even the cochlea (Bidelman et al., 2016). This enhanced encoding translates in better performance in tasks related to pitch perception (e.g. Brattico et al., 2001; van Zuijen et al., 2004), rhythm (e.g. van Zuijen et al., 2004) and melody (e.g. Fujioka et al., 2005). Many researchers have investigated whether the enhanced encoding of sound in musicians extends to SIN perception. Some studies showed an advantage for musicians compared to control groups of non-musicians in SIN tasks (e.g. Başkent & Gaudrain, 2016, Clayton et al., 2016; Parbery-Clark, 2009; Parbery-Clark, 2011; Swaminathan et al., 2015; Yoo and Bidelman, 2019), while others did not (e.g. Boebinger et al., 2015; Coffey et al., 2016; Fuller et al., 2014; Madsen et al., 2017, 2019; Ruggles et al., 2014; Yeend et al., 2017; Zendel & Alain, 2012). Studies that used HINT to estimate SIN performance reported a small advantage for young musicians with normal hearing (≤15 dB HL from 250-8000 Hz) in the noise front condition, but not for the noise side condition in (Parbery-Clark et al., 2009; Parbery-Clark et al., 2011). Generally, if an advantage for SIN is seen for musicians, it is often small and based on a small sample size (12 to 18 musicians).

A few studies have investigated the association among noise exposure, years of music training, and SIN scores. Some have found that years of music training are positively correlated with SIN scores, and noise exposure history is negatively correlated with SIN scores (Skoe et al., 2019; Ruggles et al., 2014; Coffey et al., 2016). However, other studies reported inconclusive evidence about the relationship between SIN and either of these factors (e.g. Yeend et al., 2017). For example, Yeend et al. (2017) investigated the association between noise exposure and SIN perception of 122 participants (age range = 30-57). Previous noise exposure was assessed using a series of online surveys that gathered detailed information on previous noisy occupational settings, leisure activities and use of hearing protection (Beach et al., 2013; Williams et al., 2015). Their test battery included extensive audiometric testing (e.g. tympanometry, audiometry, acoustic reflexes, otoacoustic emissions, and medial olivocochlear responses), temporal and spectral processing (i.e. detection of amplitude modulation and temporal fine structure), SIN tests as well as attention and memory evaluations. Their SIN test consisted of one condition of the Listening in Spatialized Noise-Sentences test (LiSN-S; Cameron et al., 2006) in which speech was spatially separated from background noise by 90 degrees. Their results did not show a link between lifetime noise exposure and performance on any of the temporal and spectral processing tasks nor the SIN test. Musical training was associated with better performance on temporal and spectral processing tasks, but it was not correlated with SIN perception. In fact, their results suggest that working memory, attention, and extended high-frequency thresholds were more important factors than musical training for SIN processing.

The findings of previous studies on SIN perception in musicians have a number of limitations. First, most studies used a small sample size of listeners. If using hypothesis testing, a small sample size can increase the likelihood of a Type I error -that is, the null hypothesis is rejected even though there is no actual difference between groups (Batterham & Atkinson, 2005). Second, the SIN tasks differed in terms of target stimuli (e.g. syllables, words, sentences) and background noise (e.g. speech-shaped noise, speech babble). Individual performance on these tests depends on the difficulty level of the speech materials, making comparisons between studies difficult (Duncan & Aarts, 2006). Third, several studies did not include outer hair cell assessments such as DPOAE or EHFs. A positive relationship has been found between outer hair cell function and speech perception performance in quiet and noise (e.g. Hoben et al., 2017). These limitations and differences across studies make generalizability, replicability and comparisons a challenge.

1.4 Purpose of the study

Several researchers have suggested that ANFs with a high threshold and low-SR may be affected by excessive noise exposure, even when hearing thresholds at conventional frequencies (250-8000 Hz) remain unaffected. CS in humans may lead to difficulties perceiving temporal cues as ANFs with a high threshold and low-SR may be the most vulnerable to excessive noise exposure (Bharadwaj et al., 2014; Lopez-Poveda & Barrios, 2013). Damage to these ANFs could be especially apparent in situations with low SNRs, such as in speech recognition in noise. The objective of the current study was to investigate the functional consequences of CS by comparing an at-risk group of student musicians with a control group with little-to-no musical training. Information was collected on previous noise exposure using the NESI questionnaire, a structured interview about lifetime noise exposure. To investigate monaural temporal resolution, we used the RGDT with broadband noise stimuli. Previous literature on gap detection thresholds for young adults with normal hearing show thresholds between 2 and 5 ms. Should the musician group show temporal processing difficulties, we expect higher thresholds for those participants in comparison to the control group. A functional assessment of temporal acuity was also carried out using an experimental version of the HINT, which offered the opportunity to independently use ITD and ILD cues for separating the perceived location of speech materials from noise. The noise-front (NF) condition (speech and noise lateralized at the same location within the head), was expected to result in higher thresholds (in dB SNR) than the noise-side (NS) condition (speech spatially separated from noise). Speech reception thresholds (in dB SNR) were predicted to be lower for the ILD-only and ITD-only conditions than for the NF condition, but higher compared to the NS (when both ITD and ILD cues were available). A decrease in one's ability to detect small ITDs between the two ears could lead to 'added processing noise' (van der Heijden & Trahiotis, 1999), which in turn would require an increase in signal level to allow accurate speech perception. It was predicted that musicians may have more difficulty in the ITD-only condition, which is likely more reliant on temporal processing, than in the ILD-only condition. The association between SIN performance on the ITD condition and previous noise exposure was also explored.

Chapter 2: Method

2.1 Participants

There were two groups of participants. The control group consisted of 23 participants (15 females, M_{AGE} = 22.7, range = 18 to 28, SD =3) with no history of significant noise exposure or tinnitus. The experimental group consisted of 20 students from the University of British Columbia's School of Music (14 females, M_{AGE} = 21.9 years, range = 18-27, SD=2.5), with significant exposure to loud sounds through rehearsals, concerts and individual practice. Their main music instruments were voice (N=6), piano (N=3), trombone (N=3), trumpet (N=2), oboe (N=2), viola (N=1), clarinet (N=1), French horn (N=1) and piccolo (N=1). Some music students reported having tinnitus (N=3), ear infections in both ears as children requiring antibiotics (N=4), and a history of concussion (N=1). They reported listening to personal listening devices at volumes of 82% or less. Information on participant characteristics is provided for the musician and non-musician groups in Table 2.1.

Table 2.1 Participant characteristics

	Age (years)	Sex	Ethnicity
Musicians	Mean = 23 (3) Range = 18-28	14 females 6 males	Caucasian (11) Asian (7) Indigenous (1) Other (1)
Controls	M_{AGE} = 22 (2.5) Range = 18-27	15 females 7 males	Caucasian (4) Asian (13) Indigenous (2) Mixed (3)

2.1.1 Inclusion criteria

To be included in the study, all participants needed to have: (1) normal pure-tone thresholds at conventional frequencies (i.e. <25 dB HL from 250-8000 Hz), (2) no large asymmetry in hearing thresholds between the two ears from 250-8000 Hz (i.e. <15 dB HL difference), (3) normal middle-ear function established through immittance testing, (4) normal outer hair cell function at 4 kHz established through DPOAE testing, (5) be fluent in English (due to the linguistic nature of some tests), and (6) be between the ages of 18-28. In addition to the above-mentioned criteria, the control group had to meet the following: (1) listen to their personal listening devices at volumes of 60% or less in accordance with the World Health Organization (2015), (2) no reported hearing difficulty, (3) no history of noise exposure through work, hobbies or military, (4) no previous history of head injuries, ear infections or ear surgery, and (5) no asymmetry in hearing thresholds between 9 and 16 kHz (<15 dB HL difference between the two ears).

2.1.2 Recruitment

The participants of this study were all students recruited through circulation of the study details by the University of British Columbia Faculty members and online postings. This study was approved by the University of British Columbia Ethics Committee (#H16-02052).

2.2 Procedure

2.2.1 Overview

This study was a part of a larger study taking place in the Middle Ear Lab at the University of British Columbia (see appendix A for the full protocol). Participants took part in three testing sessions. Prior to the first session of testing, all participants completed an online or paper questionnaire to determine their eligibility based on their previous noise exposure and listening habits. The first testing session began by obtaining written consent from participants, followed by a series of tests to determine eligibility such as otoscopy, tympanometry, middle-ear reflexes, conventional and extended high-frequency audiometry (250 Hz to 16 000 Hz), and otoacoustic emissions. If participants met the inclusion criteria, the following testing sessions were scheduled. The HINT test was part of the second session that took approximatively one hour to complete. This session also included the random gap detection test (RGDT; Keith, 2000), the Digit Triplet test (DT; Rudmin, 1987), and the temporal modulation transfer function test (TMTF; Viemeister, 1979). The third session consisted of the NESI and electrocochleography. All behavioral testing was conducted in a sound-treated booth that met minimum ambient noise level requirements (ISO 8253-1:2010) with appropriately calibrated audiometric equipment (ANSI S3.6, 2004). The current dissertation focuses on the results of the NESI, the HINT, and the RGDT.

2.2.2 Lifetime Noise Exposure

Participants' previous noise exposure was assessed through a structured interview, the NESI (Guest et al., 2018). This interview explores all activities the participant has experienced as noisy across their lifetime by gathering information on each activity in terms of: i. years of exposure (Y), ii. weeks per year of exposure (W), iii. days per week of exposure (D), iv. hours per day of exposure (H), v. the proportion of time hearing protection was worn (P), vi. the estimated sound level based on vocal effort (L), and vii. attenuation of hearing protection in dBA based on type used (A). The information collected through the interview was used to calculate a lifetime noise exposure metric in "units of noise exposure", where one unit is equivalent to one working year of exposure to 90 dBA. Three different formulas were used to calculate units of noise exposure, adapted to account for the use of hearing protection and the amount of noise reduction of each activity. The calculated values of noise exposure for each of the activities reported by a participant were added to obtain an estimation of their lifetime noise exposure (Guest et al., 2018). For activities in which hearing protection was used and reduced sound levels to 80 dBA or less, formula 1 was used:

$$\textit{Units of noise exposure} = \frac{Y * W * D * H}{2080} * (1 - P) * 10^{\frac{L-90}{10}} \qquad (1)$$

where

Y	years of exposure
W	weeks per year of exposure
D	days per week of exposure
H	hours per day of exposure
P	proportion of time hearing protection was worn
L	estimated sound level based on vocal effort
A	Attenuation of hearing protection in dBA based on type used

If participants used hearing protection but it did not reduce levels to 80 dBA, formula 2 was used to calculate the unit of noise exposure:

$$\textit{Units of noise exposure} = \frac{Y * W * D * H}{2080} * \left(P * 10^{\frac{L-A-90}{10}} + (1 - P) * 10^{\frac{L-90}{10}}\right) \qquad (2)$$

Formula 3 was used when activities did not involve the use of hearing protection:

$$\textit{Units of noise exposure} = \frac{Y * W * D * H}{2080} * 10^{\frac{L-90}{10}} \qquad (3)$$

2.2.3 The hearing-in-noise test

The HINT is an adaptive test developed to measure speech reception thresholds in quiet and noise. The sentences used in HINT take into account the lexical status of the words, grammatical complexity and length of utterances, all of which can affect intelligibility (Luce et al., 1990). These sentences were produced by a professional voice actor to control speaking rate, clarity and naturalness of the voice. The current study used the “adaptive HINT” method, in which the level of the masking noise was kept constant at 65 dB (A) whereas sentences varied in level. Participants were given the following written instructions to ensure consistency across experimenters:

> “This is a test of your ability to understand speech in noise. Throughout the test, you will hear a man reading sentences in some background noise. The loudness of the man’s voice will change during the testing. Sometimes it will be very faint. Repeat everything you hear the man say, even when his voice is very soft. Please repeat anything that you have heard, even if it is only part of the sentence. It is all right to guess. Do not get discouraged if you find the task difficult. No one is able to repeat all of the sentences correctly. Do you have any questions about these instructions?”

The first sentence within each list was presented at the same level as the noise. After a participant’s response to the first sentence, the level was increased or decreased in 4-dB steps for the first 4 sentences, and then in 2-dB steps for the remaining sentences in a list. The response to each sentence was scored as “correct” only if a participant repeated all the words in a sentence correctly. The current study uses an experimental version of HINT that allows for independent manipulation of ITD and ILD cues by modifying the head-related transfer functions. The stimuli modifications are similar to those used by Aronoff et al. (2010). There were four conditions in this study: (1) noise presented to the front of the listener with both ITD and ILD cues (NF condition), (2) noise presented at 90° or 270° azimuth with both ILD and ITD cues (NS condition), (3) noise presented to 90° or 270° azimuth using ILD cues only (ILD condition), and

(4) noise presented to 90° or 270° azimuth using ITD cues only (ITD condition). The NS condition was based on recordings taken from an ear canal microphone in a Knowles Electronics Manikin for Acoustic Research (KEMAR) in sound field. These recordings were used to calculate head-related transfer functions that incorporated the effects of various binaural cues. At 180° azimuths, the level and phase differences between the two ears are null. The ILD condition was created by removing ITD cues, using identical phase responses for both ears derived from a recording of noise at 180° azimuth. Similarly, the ITD condition was created by using ILDs for a noise source located at 180° azimuth.

HINT was presented via a Lenovo laptop computer connected to an Otometrics Madsen Astera² audiometer using a stereo to 2 RCA audio cable. The volume of the laptop was set to 100%. HINT calibration was done prior to testing the first participant, and halfway through testing using the HINT calibration tone (1 kHz at 100 dB SPL). The output of HDA200 circumaural headphones was measured with a Larson Davis sound level meter and the dial volume was adjusted in the Otosuite software (v.4.80.00, GN Otometrics™) to obtain a value on the sound level meter as close to 100 dB SPL as possible. Prior to the arrival of each participant, the presentation dials were adjusted through Otosuite to ensure appropriate output with values obtained at the time of calibration. A biological check was conducted prior to the second testing session of each participant to verify that selecting 'noise right' or 'noise left' translated into the appropriate output. The HINT sentences are based on the Bamford-Kowal-Bench sentences designed for speech assessment of British children. Nilsson et al. (1994) adapted these sentences by removing British idioms and usages that are less familiar to North American English listeners. HINT sentences are at a grade one level to ensure that lexical knowledge has a minimal effect on the outcome of the test. The masking noise used in HINT consists of a long-term average spectrum of all the American English sentences recorded for this test (Nilsson et al., 1994). Nilsson et al. (1994) used the frequency responses of the long-term average spectrum to generate a filter through which white noise was passed. For all HINT conditions in the present study, speech was presented to the front of the listener (0° azimuth). First, two lists of sentences (i.e. trials) were presented for the NF condition. Subsequently, the NS, ILD, and ITD conditions were presented. Table 2.2 summarizes the masking noise location and spatial cues present in each condition.

Table 2.2 HINT conditions

Shaded rows indicate trials that were conducted only if the SNR standard deviation of trial 1 was over 2.0 dB.

Condition	Trial	Masking noise	Spatial cues
NF	1	Front	Interaural level and time differences
NF	2	Front	Interaural level and time differences
NS	1	Side	Interaural level and time differences
NS	2	Side	Interaural level and time differences
ILD	1	Side	Interaural level differences
ILD	2	Side	Interaural level differences
ITD	1	Side	Interaural time differences
ITD	2	Side	Interaural time differences

At the end of each trial, the HINT software generated the estimated SNR at which participants could repeat back all of the words, the standard deviation of the SNR and the percentage of intelligibility (i.e. % words correct). For NS, ILD, and ITD conditions, a second trial was conducted if the standard deviation of the SNR obtained in trial 1 was 2.0 dB or above. The sentence lists, the order of NS, ILD, and ITD conditions and the side on which the noise was presented (i.e. 90° or 270° azimuth) were counterbalanced across participants. Normative HINT values, in dBs, were reported for TDH-50 headphones for the NF and NS conditions by Soli & Wong (2008). The sample consisted of 67 adults (mean age = 38.7 years) with normal hearing at octave frequencies between 250 to 8000 Hz. Participants performed better in the NS condition, where noise was presented at 90 or 270° azimuth (M_{SNR} = -10.1 dB, SD = ±1.3 dB) than in the NF condition, where noise was presented to the front (M_{SNR} = -2.6 dB, SD = ±1.0 dB).

2.2.4 The random gap detection test

The RGDT is a temporal measure frequently used to assess the temporal resolution ability of children and adults with auditory processing disorders (e.g. Balen et al., 2009). The RGDT is a revision of the Auditory Fusion Test – Revised (McCroskey and Keith, 1996), in which tones or clicks separated by silent gaps of varying duration are presented in a random order (Chermak & Lee, 2005). In the current study, a custom version of the RGDT was used in which the stimuli consisted of sequences of two bursts of broadband noise presented to the ear with a lower pure-tone average. If both ears had identical pure-tone averages, the RGDT was presented on the same side as the noise in the HINT-NS condition. The stimulus was presented through a Lenovo laptop computer connected to an Otometrics Madsen Astera[2] audiometer. Circumaural HDA200 headphones were used. The presentation level was set to the added value of their pure-tone average for that ear and 50 dB HL. All participants took part in a training phase where they were presented with 6 trials with gap durations of either 0- or 40-ms intervals. The experimental phase included a total of 150 trials with gap durations of 0, 2, 4, 6, 8, 10, 12, 16, and 20 ms. The task took approximatively 10 minutes to complete. The output of the RGDT software gives access to a list of responses for each of the silent intervals. The gap detection threshold was selected as the smallest silent interval for which a listener perceived a gap (two noise bursts) over 70% of the time.

2.3 Data analysis

A Bayesian approach was selected for the data analysis (the raw data are included displayed in the Appendix). Bayesian inference is well equipped to analyze datasets with a small sample size, as a model is developed based on the parameters of the model and observed data, and is valid for any sample size (Hox et al., 2012; Lee and Song, 2004). The objective of Bayesian modelling is to redistribute credibility of parameter values into posterior distributions using the observed data (Kruchke & Liddel, 2018). Statistical analyses were conducted using the R statistical programming language (R Core Team, 2017) with the "rethinking" package (McElreath, 2020). This package uses a Markov Chain Monte Carlo (MCMC) sampler implemented in the Stan statistical programming language (Carpenter et al., 2017). An additional linear model was fit to investigate NESI as predictor variables with HINT SNR as the outcome variable. The optimal amount of regularization for priors was chosen by conducting sensitivity analyses. The selected model for the main analysis used a Student likelihood distribution with 5 degrees of freedom. The model intercept had a normal prior with mean = 0 and SD = 1. The prior distribution for the conditions within each group was set as normal with mean = 0 and SD = 0.35.

Chapter 3: Results

3.1 Noise Exposure Structured Interview

Estimated lifetime noise exposure was obtained by summating estimated units of noise exposure for each activity. Figure 3.2 illustrates the distribution of NESI scores for the musicians and controls.

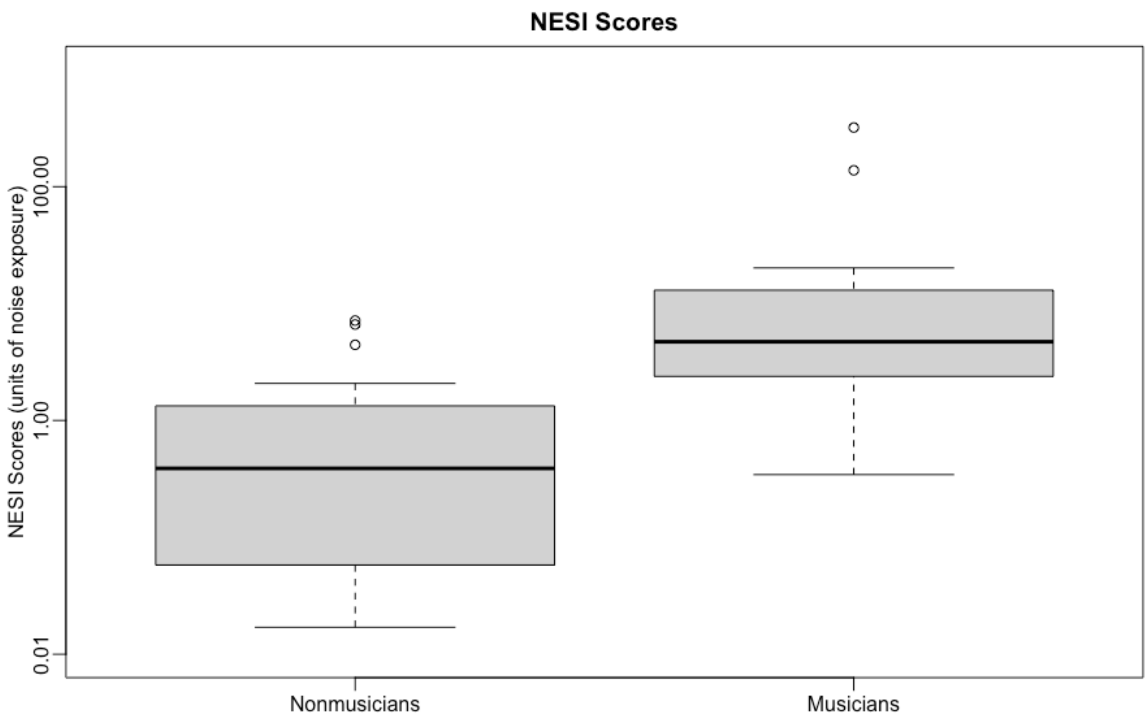


Figure 3.2 Boxplot of lifetime noise exposure estimated through NESI. Minimum, first quartile, second quartile (i.e. median), third quartile, maximum and outliers of the data set are represented.

The limits of the first quartile and third quartile of the data for each group are represented as the grey shaded box. There is no overlap between this portion of the data for two groups, which illustrates that most musicians had higher estimated noise exposure. The model used was a robust Bayesian analogue of a classic t-test with a Student's t distribution as the likelihood function and log of NESI as the outcome variable. The use of a Student t likelihood function for two-group comparison is suitable for analyzing data sets that are likely to contain outliers (Kruschke, 2011). The prior for the group means was normally distributed with a mean = 0 and a SD estimated from the sample as a hyper parameter. The priors for all SD parameters and for the shape parameter (also called "degrees of freedom") of the Student-t likelihood were distributed as Exponential(1). The full model description is available in the Appendix. A visual check of the chain showed no abnormalities. Each parameter converged with a number of effective samples of 8000 or larger. The marginal posterior of the difference in the mean NESI scores between the two groups had a mean of 2.3 [1.42, 3.25]. The marginal posterior of the effect size for the difference between the two groups was calculated in a similar way to Cohen's d, and was large (1.6); there was a 94.5% probability that the effect size was larger than 1 (UI = [1, 2.6]). Thus, the model is very confident that the two groups differ in terms of estimated lifetime noise exposure.

3.2 Random gap detection test

A gap detection threshold was obtained for each participants' better ear. The data for one musician and four controls are missing because of a programming error. All participants obtained thresholds of 4 ms, with the exception of 2 musicians who obtained thresholds of 2 ms. Given the lack of variability in these data, no further analysis was performed on the RGDT data.

3.3 Hearing-in-noise test

Musicians and controls were tested on four conditions of the HINT: (1) noise presented to the front of the listener using both ITD and ILD cues (NF), (2) noise presented to one side using both ILD and ITD cues (NS), (3) noise presented to one side using ILD cues only (ILD) and (4) noise presented one the side using ITD cues only (ITD). Figure 3.3 shows HINT scores across groups and conditions. Although the SNRs of the control group in the ITD condition appear to have more variability, there is a large amount of overlap between the experimental and control group across all conditions. SNR values were generally more variable for the NS, ITD and ILD conditions than for the NF condition.

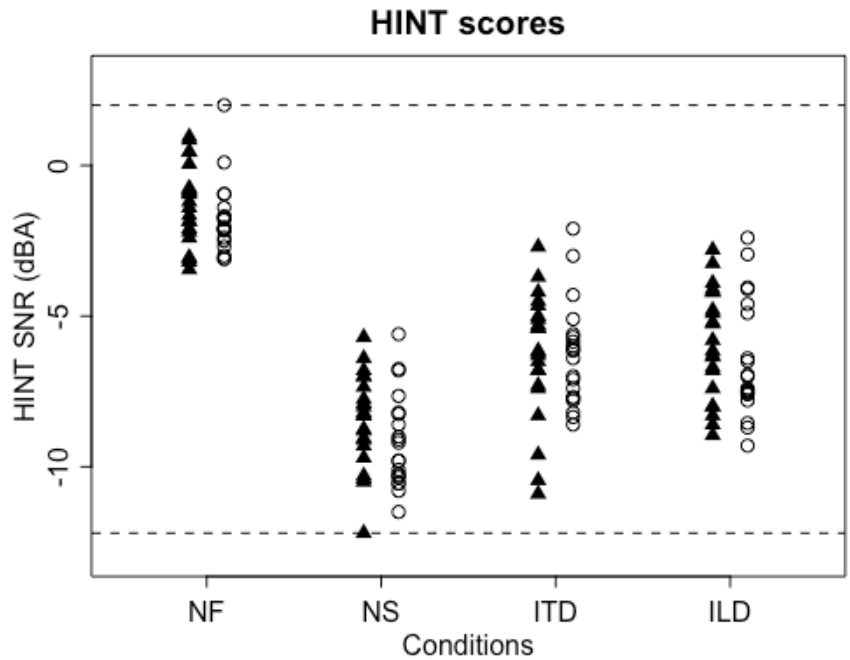


Figure 3.3. Standardized HINT SNRs across groups and conditions. Filled triangles illustrate the HINT scores obtained for the control group whereas circles indicate scores of the musician group. Dotted lines correspond to minimum and maximum values. A lower SNR corresponds to a better score on the HINT.

SNR values were transformed into z-scores to facilitate the convergence of the MCMC process used to calculate the posterior of the Bayesian statistical analysis. A multilevel linear regression model with noncentered parameterization was fit with standardized HINT scores as the outcome variable. The model included varying intercepts for listeners. Although it would have been desirable to include varying slopes for listeners by condition, it was not possible to get the MCMC sampling to converge due to limited data points (one HINT score per condition for each participant). The likelihood function was a Student's t distribution with 5 degrees of freedom. The linear model included fixed effects for condition (NF, NS, ITD, ILD) and group (musician and control participants). The prior distribution for the model intercept was defined as a normal distribution with mean = 0 and SD = 1. The prior distribution for the conditions within each group was normal with mean = 0 and SD = 0.35. Each parameter converged with a number of effective samples of 8000 or larger. Chain convergence and sampling was monitored through visual examination of the traceplots and no abnormalities were detected. The sensitivity analysis showed that a more strongly regularizing prior (SD = 0.25) and a more weakly regularizing prior (SD = 0.75) for the interaction coefficient sampled less efficiently and led to parameter estimates with similar medians, but less precise UIs (see the Appendix for full description of the model, and the results of the sensitivity analysis). A posterior predictive check showed that the model's pointwise predictions were reasonably accurate for most data points (as illustrated in the Appendix). Figure 3.4 displays the posterior means for each condition of the fitted Bayesian regression model (filled triangles for control group; open circles for the musician group) and the sample mean HINT scores (blue, filled circles) for each group and condition. In this figure, bars represent the 89% uncertainty intervals. The estimates of the multilevel model, with the exception of ILD condition, are shrinked towards the overall posterior intercept of the model (displayed by the horizontal dotted line), as expected.

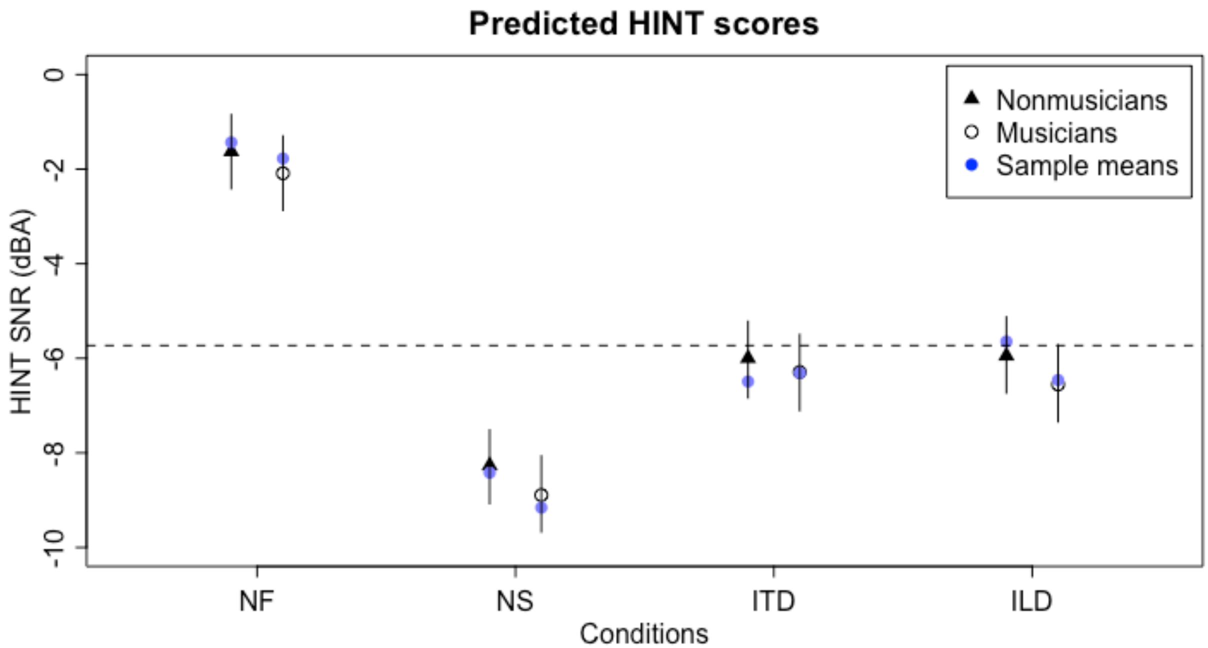


Figure 3.4. Predicted and sample means for musicians and controls. The horizontal dotted line displays the overall posterior intercept of the Bayesian model. The error bars represent the 89% uncertainty interval for each estimate.

The marginal posteriors for differences between groups and conditions are reported as means together with the smallest interval that contains 90% of the probability mass (uncertainty interval' or UI, in square brackets). Overall, there was a small advantage for the musician group in speech perception in noise (mean difference between musician and control groups = 0.5 [0, 1.0]). Group differences for each HINT condition were very small and the estimated sign of the difference (i.e. positive or negative) was uncertain (NF = 0.5 [-0.3, 1.2]; NS = 0.6 [-0.1, 1.4]; ITD = 0.3 [-0.5, 1.1]; ILD = 0.6 [-0.3, 1.4]). There were large differences between the NF and the NS conditions (mean = 6.7 [6.2, 7.2], the NF and the ITD conditions (mean = 4.3 [3.8, 4.8]), and the NF and the ILD conditions (mean = 4.4 [3.9, 4.9]). There was a smaller, but clearly negative difference between the NS and the ITD conditions (mean = -2.4 [-3.0, -1.9], and between the NS and the ILD conditions (mean = -2.3 [-2.9, -1.8]). By contrast, the difference between the ILD and the ITD conditions was very small and of uncertain sign (mean = 0.1 [-0.4, 0.7). These results indicate that participants benefitted of the separation of speech from noise, even when they could only rely on one binaural cue (ITD or ILD).

3.3.1 Hearing-in-noise test and estimated previous noise exposure

This analysis included HINT-ITD as the outcome variable and NESI and group as predictor variables. The regression model also included the interaction of NESI scores and group. The ITD condition was selected as the outcome variable as it was expected to be most affected by CS, and led to the most variability in HINT performance. The full model description and sensitivity analysis are available in the Appendix. To facilitate the convergence of the MCMC process used to calculate the posterior of Bayesian statistical analysis, SNR values were standardized and NESI scores were transformed into log values. The overall intercept and interaction coefficients were set as normal distributions with mean = 0 and SD = 1. Normal distributions with means = 0 and SD = 0.25 were used for the individual predictors of NESI and group, as well as the interaction coefficients. A visual check of the MCMC chain showed no abnormalities. The posterior showed that slope coefficients of the estimated regression line between ITD and NESI were small and of uncertain sign for both musicians (0,10 [-0.05, 0.27]) and controls listeners (0.01 [-0.11, 0.14]). Figure 3.5 shows estimated slopes and sample data for musicians and controls for HINT-ITD as the outcome variable.

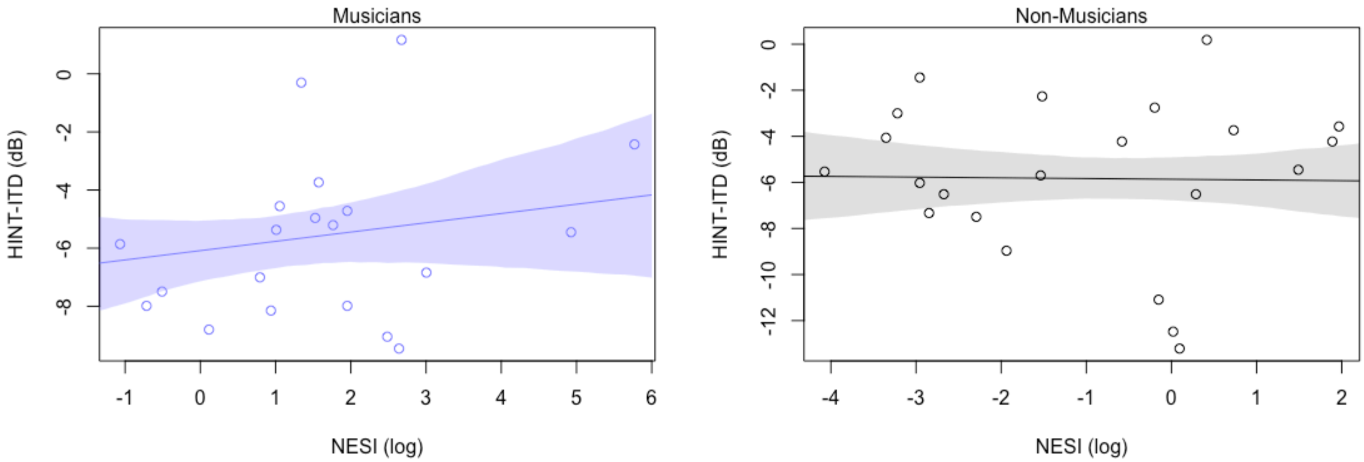


Figure 3.5 Estimated slopes and sample data for HINT-ITD and NESI regression analysis.

Mean estimated regression line with 89% probability uncertainty intervals (shaded areas) for HINT-ITD as the outcome variable for musicians (left panel) and control listeners (right panel).

Chapter 4: Discussion

There is emerging evidence that CS may occur in humans (Liberman et al., 2016) and cause functional consequences such as difficulty with temporal coding or speech in noise perception (Furman et al., 2013; Kumar et al., 2012). The purpose of the current study was to investigate these functional consequences in an at-risk group of young student musicians using a control group with no history of excessive noise exposure. Through Bayesian modelling, our results show a high degree of confidence that the musician group had higher estimated lifetime noise exposure than the control group. There was also a small advantage for the musician group in HINT scores, but the uncertainty interval was relatively large. Participants in the current sample had lower HINT scores for the NS condition in comparison to the NF condition. Similarly, differences were found between the NF and ITD conditions and between the NF and ILD conditions, indicating that participants likely benefitted from the separation of speech from noise, even with limited access to binaural cues. Differences between the ILD and ITD conditions were very small and of uncertain sign, indicating that participants in this sample likely benefitted equally from both spatial cues. Similarly, the association between HINT-ITD and estimated lifetime noise exposure was uncertain for the control and musician group.

4.1 Noise Exposure Structured Interview

As expected, the musicians in this sample had higher estimated lifetime noise exposure. The NESI has been used previously in a pilot study evaluating music industry workers' noise exposure (Dewey et al., 2018) and in CS studies (e.g. Guest et al. 2018). In non-music industry workers, the range of values found in these previous studies was wider (between ~0.01-100 units of noise exposure) than the current study (0.02-7.2 units of noise exposure). The music group in Dewey et al. (2018) obtained values between approximatively between 4 and 300 units of noise exposure, whereas the current results show lower bound of values (between 0.34 – 320 units of noise exposure). One possible reason for these differences lies in the age of participants. The participants in the current study were younger (between 18 and 28 years of age) than those in previous studies using the NESI (between 18 and 40 years of age).

4.2 Random gap-in-noise test

In light of previous literature, musicians were expected to obtain higher gap detection thresholds than controls, as higher noise exposure could lead to impaired temporal resolution. Our results show similar gap detection performance for both groups, suggesting that the musician group does not have impaired temporal acuity as estimated through this test. Results in the current study are comparable to those of Roberts & Lister (2004) and Musiek et al., (2005), who obtained gap detection thresholds between 2 and 4.9 ms for young adults with normal hearing thresholds. The young musicians in the current sample were between the ages of 18 to 28. It is possible that a longer period of noise exposure is required to lead to a measurable loss of temporal acuity.

4.3 Hearing-in-noise test performance as a function of localization cues and noise exposure

The prediction for HINT was the following: if noise exposure results in impaired temporal processing, then musicians could have lower SNRs than controls when using ITD cues for speech perception. Our findings did not demonstrate a difference between groups for any of the HINT conditions. A difference was found between the NF condition in comparison to the NS, ITD and ILD conditions. Specifically, the posterior of the Bayesian model indicated a 100% probability that listeners perform worse in the NF condition than in the NS, ITD or ILD conditions. This finding is consistent with those of other studies using the HINT-NF and NS conditions in which the separation of speech from noise leads to better SIN perception (e.g. Culling et al., 2004; Nilsson et al., 1994; Parbery-Clark et al., 2009). Participants in Soli & Wong's (2008) study also performed better in the NS condition (M_{SNR} = -10.1 dB, SD = ±1.3 dB) than in the NF condition (M_{SNR} = -2.6 dB, SD = ±1.0 dB). The participants in Soli & Wong's (2008) study were native English speakers, whereas our sample included bilingual speakers whose first language was not English. The similarity between previous norms and the current results indicates that the bilingualism of the listeners in the current study likely did not adversely affect our results.

In contrast with Culling et al. (2004), who found that listeners with no reported hearing difficulties benefitted more from ITD cues over ILD cues, the current study did not find a difference between the two conditions. Differences in the stimuli used and participant characteristics could explain the contrasting results. The main stimuli in Culling et al. (2004) consisted of the Harvard sentence list, which contains sentences that are less predictable (e.g., "The small pup gnawed a hole in the sock") than HINT sentences. The participants who took part in the study by Culling and colleagues were college students with no reported hearing difficulties. By contrast, seven music students and five control listeners in the current study reported hearing difficulties in loud environments or when the speaker "mumbles". It is difficult to determine if hearing sensitivity or age differences could explain the discrepancy, as no audiometric testing was conducted and the mean age of participants were not reported.

The current results support the growing literature on CS in which a noise-exposed group and control group obtain similar SIN scores (e.g. Fulbright et al., 2017; Yeend et al., 2017) as well as the literature on musicians' SIN perception where no differences between groups are found for SIN perception (e.g. Ruggles et al., 2014; Yeend et al., 2017). Our results contrast with the findings by Liberman and colleagues (2016) who found a difference in SIN performance between the at-risk group and control group. A number of factors could explain this difference. First, the inclusion criteria in the current study were stricter than those in Liberman et al. (2016). In addition to having normal hearing and unremarkable otoscopic examinations, the control group in the current study was screened for outer hair cell dysfunction through DPOAEs, had no history of head injuries, or excessive use of personal listening devices. Factors such as outer hair cell function, head injuries and excessive use of personal listening devices have all been associated with difficulties perceiving SIN and could contribute to the lower SRTs seen in the music group (Gilliver et al., 2017; Hoben et al., 2017; Thompson et al., 2018). Second, Liberman et al. (2016) found a difference between the two groups in EHF results, where the at-risk group had higher EHF thresholds. As mean and standard deviation are not provided in the paper for each group individually, it is difficult to determine if age had an impact on extended high-frequency threshold results. However, the age range of the participants in the current study is more constrained (18 to 28 years of age) than in the study by Liberman and colleagues (18 to 41 years of age). As aging also has an effect on the auditory system (e.g. loss of ANF fibers; see, for example, Makary et al., 2011) and the auditory system generally, it is possible that the effect seen in Liberman et al. (2016) is both age-related and noise-induced. Furthermore, the current study had strictly student musicians in the at-risk group and a more extensive measure of noise exposure. Having stricter inclusion criteria and a more representative measure of noise exposure may increase homogeneity in the sample population, and optimize external and internal validity (Patino & Ferreira, 2018). Homogenous samples are important in the current context of CS studies, as the objective is often to find a test that is sensitive to the condition.

In the current study, the similar performance between groups in the HINT could be explained by the following reasons: (1) the HINT test may not be sensitive enough as a screening tool for CS, (2) the at-risk group in the current study did not have sufficient noise exposure to observe functional impairments due to CS, (3) CS is not as widespread in humans as previously thought or (4) the presence of an interactions between noise exposure and an advantage for sound processing in musicians. First, it is possible that HINT conditions used in this study were not sensitive to CS due to noise overexposure. However, this possibility is unlikely as the HINT has been validated to predict speech intelligibility in a wide range of communication environments, including as a measure of functional hearing for hearing-critical jobs (Giguere et al., 2008). Second, it is likely that the at-risk group in the current study did not have sufficient noise exposure to see functional impairments due to CS. The few studies who explored CS in older participants found reductions in wave I ABR (Gu et al., 2012; Schaette & McAlpine, 2011; Valderrama et al., 2018). In Schaette and McAlpine, the experimental group consisted of 15 participants with tinnitus ($M_{AGE} = 36.3 \pm 2.6$) and 18 controls ($M_{AGE} = 33.2 \pm 1.9$). The experimental group showed a reduction in ABR wave I amplitude, which either suggests a reduction in number of responsive ANFs, reduced synchrony in the discharge of the ANFs, or both. Thus, an older age group consists of an interesting avenue for CS research, especially to explore functional deficits in SIN perception. Third, it is possible that CS alone, with no permanent hearing threshold shift, may not be as widespread in humans as previously thought. Currently, noise exposure parameters such as level and duration needed to see CS in humans remain unknown (Kujawa & Liberman, 2019). Animal models allow for rigorous control of high-level noise exposure, whereas humans may have varying degrees of exposure within the experimental group. The range for CS is very narrow. In animal models, decreasing the sound presentation level by 3 dB eliminates CS whereas increasing the level by 3 dB leads to permanent hearing threshold shifts in addition to CS (Bramhall et al., 2019). Furthermore, animal studies with macaque monkeys show that they are more resistant to CS than rodents (Valero et al., 2017). Similar noise exposure led to 12-27% loss of synapses in monkeys and 40-55% loss in rodents (Kujawa & Liberman, 2009; Lin et al., 2011; Hickox et al., 2017). If humans are less vulnerable to noise-induced CS, it may be difficult to uncover it without other types of noise-induced hearing loss. Fourth, a possible explanation lies in the interaction of noise exposure and a musician advantage for SIN perception. The current data does not allow for an investigation of both factors, as data on the onset/years of music training was not collected. Even if music training offers some protection against the detrimental effects of noise exposure, longer musical experience also results in increased history of noise exposure. Increased noise exposure could counter the previous effect and eventually become a measurable SIN disadvantage for musicians (Skoe, Camera & Turfs, 2018). In the current study, a Bayesian regression model showed a very weak associations of uncertain sign between the estimated of lifetime noise exposure and HINT-ITD SNRs. Further research should be conducted to explore the association between noise exposure and speech perception performance in older musicians who have a longer history of noise exposure than the musicians who participated in the current study.

4.4 Study limitations

One limitation often seen in behavioral studies measuring SIN perception is the use of a small sample size. The current study had 20 participants in the music group and 22 participants in the control group. Although Bayesian modelling is more robust to the effects of a small sample size than traditional statistics (Hox et al., 2012; Lee and Song, 2004), the model in the main analysis could be improved by including varying slopes for participants in order to model differences in HINT scores by condition among participants. A multilevel model with varying slopes for listeners by condition would have been ideal, but limited data points per participant did not allow the MCMC chain to converge. Another limitation to consider is the use of a self-report measure for the estimation of lifetime noise exposure. Although determining dB levels based on vocal effort has been validated, any self-report measure is prone to measurement errors (e.g. Ferguson et al., 2019). Ferguson et al. (2019) found that 91% of participants reported noise levels based on vocal effort within 6 dB of the direct measurement. The dB scale being a logarithmic scale, an underestimation of 6 dB corresponds to underestimating four times the quantity of acoustic energy. This is reflected in the calculation of units of noise exposure for an activity. For instance, a noisy activity done 3 times per week for 5 years at 99 dB corresponds to 8.25 units of noise exposure, whereas the same activity at 105 dB finds an estimated 32.8 units of noise exposure. Underestimating by 6 dB thus makes a considerable difference in the calculations of units of lifetime noise exposure. A second measurement error could be introduced if participants accidentally omit noisy recreational or occupational activities. Future studies could use of a combination of indirect self-reporting and direct measures of sound exposure, such as an in-ear dosimetry.

4.5 Conclusion and future directions

Early research on CS in humans has many gaps and more research should be conducted to find (1) measures of noise exposure that are more representative of an individual's lifetime noise exposure, (2) behavioral tests with good sensitivity and specificity to reliably diagnose CS in humans, (3) the amount of noise exposure needed to observe CS in humans, (4) the presence or absence of an interaction between noise exposure and music training, (5) other factors that are important to control for when investigating CS in humans, and (6) changes over time on a broad range of auditory assessments, including tests of temporal acuity. The current study attempted to fill some of these gaps of knowledge by using two behavioral tests, the HINT and RGDT, to investigate the functional consequences in an at-risk group of music students. No differences between groups were found for any of the HINT conditions or the RGDT. It is possible that the young music student sample did not have sufficient noise exposure to lead to temporal processing difficulties due to CS. Given the current literature on CS in humans, strict inclusion criteria, broad research protocols and interdisciplinary collaborations are warranted, as peripheral auditory processes (e.g. outer hair cell function) and central factors (e.g. attention, personality) must be controlled for. The current study could be developed further by testing older musicians with normal hearing thresholds at conventional frequencies, or by conducting a longitudinal study to see the trajectory of change. Should the HINT be used in future studies, it would be important to determine the extent to which an ITD-detection threshold task relates to the HINT-ITD condition and thus, determine if that particular condition consists of an accurate measure of temporal processing. The use of a direct measure of occupational noise exposure, such as dosimetry, could complement self-reports of lifetime noise exposure. Typically, hearing conservation programs use pure-tone audiometry for monitoring purposes based on the premise that, if audiometric thresholds at conventional frequencies are less or equal to 20 dB HL, then no damage to the auditory system is suspected. A revision of hearing conservation programs and policy is warranted if noise exposure can induce CS and difficulties with temporal processing, which would go undetected in existing programs.

References

Alvord, L. S. (1983). Cochlear dysfunction in" normal-hearing" patients with history of noise exposure. *Ear and hearing*, *4*(5), 247-250.

Arbogast, T. L., Mason, C. R., & Kidd Jr, G. (2002). The effect of spatial separation on informational and energetic masking of speech. *The Journal of the Acoustical Society of America, 112*(5), 2086-2098.

Arenas, J. P., & Suter, A. H. (2014). Comparison of occupational noise legislation in the Americas: an overview and analysis. *Noise and Health*, *16*(72), 306.

Aronoff, J. M., Yoon, Y. S., Freed, D. J., Vermiglio, A. J., Pal, I., & Soli, S. D. (2010). The use of interaural time and level difference cues by bilateral cochlear implant users. *The Journal of the Acoustical Society of America*, *127*(3), EL87-EL92.

Balen, S. A., Liebel, G., Boeno, M. R. M., & Mottecy, C. M. (2009). Resolução temporal de crianças escolares. *Revista Cefac*, *11*, 52-61.

Başkent, D., & Gaudrain, E. (2016). Musician advantage for speech-on-speech perception. *The Journal of the Acoustical Society of America*, *139*(3), EL51-EL56.

Batterham, A. M., & Atkinson, G. (2005). How big does my sample need to be? A primer on the murky world of sample size estimation. *Physical Therapy in Sport*, *6*(3), 153-163.

Beach, E. F., Gilliver, M., & Williams, W. (2013). Leisure noise exposure: Participation trends, symptoms of hearing damage, and perception of risk. *International Journal of Audiology*, *52*(sup1), S20-S25.

Bernard, M., Chang, C., Ghane, G., Head, T., Kore, S., Lombardo, N., ... & Sigurdson, J. Research Project: Hidden Hearing Loss in Music Students. *Canadian Audiologist*, *6*(2).

Bernstein, L. R., & Trahiotis, C. (2015). Converging measures of binaural detection yield estimates of precision of coding of interaural temporal disparities. *The Journal of the Acoustical Society of America*, *138*(5), EL474-EL479.

Bernstein, L. R., & Trahiotis, C. (2016). Behavioral manifestations of audiometrically-defined "slight" or "hidden" hearing loss revealed by measures of binaural detection. *The Journal of the Acoustical Society of America*, *140*(5), 3540-3548.

Bharadwaj, H. M., Masud, S., Mehraei, G., Verhulst, S., & Shinn-Cunningham, B. G. (2015). Individual differences reveal correlates of hidden hearing deficits. *Journal of Neuroscience*, *35*(5), 2161-2172.

Bharadwaj, H. M., Verhulst, S., Shaheen, L., Liberman, M. C., & Shinn-Cunningham, B. G. (2014). Cochlear neuropathy and the coding of supra-threshold sound. *Frontiers in systems neuroscience*, *8*, 26.

Bianchi, F., Carney, L. H., Dau, T., & Santurette, S. (2019). Effects of musical training and hearing loss on fundamental frequency discrimination and temporal fine structure processing: Psychophysics and modeling. *Journal of the Association for Research in Otolaryngology*, *20*(3), 263-277.

Bidelman, G. M., & Alain, C. (2015). Musical training orchestrates coordinated neuroplasticity in auditory brainstem and cortex to counteract age-related declines in categorical vowel perception. *Journal of Neuroscience*, *35*(3), 1240-1249.

Bidelman, G. M., & Krishnan, A. (2010). Effects of reverberation on brainstem representation of speech in musicians and non-musicians. *Brain research*, *1355*, 112-125.

Bidelman, G. M., Krishnan, A., & Gandour, J. T. (2011). Enhanced brainstem encoding predicts musicians' perceptual advantages with pitch. *European Journal of Neuroscience*, *33*(3), 530-538.

Bidelman, G. M., Nelms, C., & Bhagat, S. P. (2016). Musical experience sharpens human cochlear tuning. *Hearing Research*, *335*, 40-46.

Boebinger, D., Evans, S., Rosen, S., Lima, C. F., Manly, T., & Scott, S. K. (2015). Musicians and non-musicians are equally adept at perceiving masked speech. *The Journal of the Acoustical Society of America*, *137*(1), 378-387.

Bourien, J., Tang, Y., Batrel, C., Huet, A., Lenoir, M., Ladrech, S., ... & Wang, J. (2014). Contribution of auditory nerve fibers to compound action potential of the auditory nerve. *Journal of neurophysiology*, *112*(5), 1025-1039.

Bramhall, N., Beach, E. F., Epp, B., Le Prell, C. G., Lopez-Poveda, E. A., Plack, C. J., ... & Canlon, B. (2019). The search for noise-induced cochlear synaptopathy in humans: Mission impossible? *Hearing Research*, *377*, 88-103.

Bramhall, N. F., Konrad-Martin, D., McMillan, G. P., & Griest, S. E. (2017). Auditory brainstem response altered in humans with noise exposure despite normal outer hair cell function. *Ear and hearing*, *38*(1), 1-12.

Brattico, E., Näääätäänen, R., & Tervaniemi, M. (2001). Context effects on pitch perception in musicians and nonmusicians: Evidence from event-related-potential recordings. *Music Perception*, *19*(2), 199-222.

Büchler, M., Kompis, M., & Hotz, M. A. (2012). Extended frequency range hearing thresholds and otoacoustic emissions in acute acoustic trauma. *Otology & neurotology*, *33*(8), 1315-1322.

Cameron, S., Dillon, H., & Newall, P. (2006). Development and evaluation of the listening in spatialized noise test. *Ear and hearing*, *27*(1), 30-42.

Canadian Centre for Occupational Health and Safety. (2016, July 24). *Noise – Occupational Exposure Limits in Canada*. https://www.ccohs.ca/oshanswers/phys_agents/exposure_can .html

Carhart, R., Tillman, T. W., & Greetis, E. S. (1969). Perceptual masking in multiple sound backgrounds. *The Journal of the Acoustical Society of America*, *45*(3), 694-703.

Carpenter, B., Gelman, A., Hoffman, M. D., Lee, D., Goodrich, B., Betancourt, M., ... & Riddell, A. (2017). Stan: A probabilistic programming language. *Journal of statistical software*, *76*(1).

Chasin, M. (2009). Hearing loss prevention for musicians and introduction to the problem. *Hearing loss in musicians: Prevention and management. San Diego: Plural Publishing*, 1-10.

Chermak, G. D., & Lee, J. (2005). Comparison of children's performance on four tests of temporal resolution. *Journal of the American Academy of Audiology*, *16*(8), 554-563.

Clayton, K. K., Swaminathan, J., Yazdanbakhsh, A., Zuk, J., Patel, A. D., & Kidd Jr, G. (2016). Executive function, visual attention and the cocktail party problem in musicians and non-musicians. *PloS one*, *11*(7), e0157638.

Coffey, E. B., Herholz, S. C., Chepesiuk, A. M., Baillet, S., & Zatorre, R. J. (2016). Cortical contributions to the auditory frequency-following response revealed by MEG. *Nature communications*, *7*(1), 1-11.

Coffey, E. B., Mogilever, N. B., & Zatorre, R. J. (2017). Speech-in-noise perception in musicians: A review. *Hearing research*, *352*, 49-69.

Culling, J. F., Hawley, M. L., & Litovsky, R. Y. (2004). The role of head-induced interaural time and level differences in the speech reception threshold for multiple interfering sound sources. *The Journal of the Acoustical Society of America*, *116*(2), 1057-1065.

Dewey, R. S., Hall, D. A., Guest, H., Prendergast, G., Plack, C. J., & Francis, S. T. (2018). The physiological bases of hidden noise-induced hearing loss: Protocol for a functional neuroimaging study. *JMIR Research Protocols*, *7*(3), e79.

Dias, K. Z., Jutras, B., Acrani, I. O., & Pereira, L. D. (2012). Random Gap Detection Test (RGDT) performance of individuals with central auditory processing disorders from 5 to 25 years of age. *International journal of pediatric otorhinolaryngology*, *76*(2), 174-178.

Di Stadio, A., Dipietro, L., Ricci, G., Della Volpe, A., Minni, A., Greco, A., ... & Ralli, M. (2018). Hearing loss, tinnitus, hyperacusis, and diplacusis in professional musicians: A systematic review. *International journal of environmental research and public health*, *15*(10), 2120.

Du, Y., & Zatorre, R. J. (2017). Musical training sharpens and bonds ears and tongue to hear speech better. *Proceedings of the National Academy of Sciences*, *114*(51), 13579-13584.

Duncan, K. R., & Aarts, N. L. (2006). A comparison of the HINT and Quick SIN tests. *Journal of Speech Language Pathology and Audiology*, *30*(2), 86.

Fausti, S. A., Frey, R. H., Erickson, D. A., Rappaport, B. Z., Cleary, E. J., & Brummett, R. E. (1979). A system for evaluating auditory function from 8000–20 000 Hz. *The Journal of the Acoustical Society of America*, *66*(6), 1713-1718.

Ferguson, M. A., Tomlinson, K. B., Davis, A. C., & Lutman, M. E. (2019). A simple method to estimate noise levels in the workplace based on self-reported speech communication effort in noise. *International journal of audiology*, *58*(7), 450-453.

Fernandez, K. A., Jeffers, P. W., Lall, K., Liberman, M. C., & Kujawa, S. G. (2015). Aging after noise exposure: acceleration of cochlear synaptopathy in "recovered" ears. *Journal of Neuroscience*, *35*(19), 7509-7520.

Freyman, R. L., Helfer, K. S., McCall, D. D., & Clifton, R. K. (1999). The role of perceived spatial separation in the unmasking of speech. *The Journal of the Acoustical Society of America*, *106*(6), 3578-3588.

Fuchs, P. A., Glowatzki, E., & Moser, T. (2003). The afferent synapse of cochlear hair cells. *Current opinion in neurobiology*, *13*(4), 452-458.

Fujioka, T., Trainor, L. J., Ross, B., Kakigi, R., & Pantev, C. (2005). Automatic encoding of polyphonic melodies in musicians and nonmusicians. *Journal of cognitive neuroscience*, *17*(10), 1578-1592.

Fulbright, A. N., Le Prell, C. G., Griffiths, S. K., & Lobarinas, E. (2017). Leisure Noise and Hearing: Effects of Recreational Noise on Threshold and Suprathreshold Measures of Auditory Function. *Seminars in hearing*, *38*(4), 298-318.

Fuller, C. D., Galvin III, J. J., Maat, B., Free, R. H., & Başkent, D. (2014). The musician effect: does it persist under degraded pitch conditions of cochlear implant simulations?. *Frontiers in neuroscience*, *8*, 179.

Furman, A. C., Kujawa, S. G., & Liberman, M. C. (2013). Noise-induced cochlear neuropathy is selective for fibers with low spontaneous rates. *Journal of Neurophysiology*, *110* (3), 577-586.

Furness, D. N., & Lawton, D. M. (2003). Comparative distribution of glutamate transporters and receptors in relation to afferent innervation density in the mammalian cochlea. *Journal of Neuroscience*, *23*(36), 11296-11304.

Giguere, C., Laroche, C., Soli, S. D., & Vaillancourt, V. (2008). Functionally-based screening criteria for hearing-critical jobs based on the Hearing in Noise Test. *International journal of audiology*, *47*(6), 319-328.

Gilliver, M., Nguyen, J., Beach, E. F., & Barr, C. (2017). Personal Listening Devices in Australia: Patterns of Use and Levels of Risk. *Seminars in hearing, 38*(4), 282-297.

Glyde, H., Buchholz, J. M., Dillon, H., Cameron, S., & Hickson, L. (2013). The importance of interaural time differences and level differences in spatial release from masking. *The Journal of the Acoustical Society of America*, *134*(2), 147-152.

Gordon, J. S., Griest, S. E., Thielman, E. J., Carlson, K. F., Helt, W. J., Lewis, M. S., ... & Henry, J. A. (2017). Audiologic characteristics in a sample of recently-separated military Veterans: The Noise Outcomes in Servicemembers Epidemiology Study (NOISE Study). *Hearing research*, *349*, 21-30.

Grinn, S. K., Wiseman, K. B., Baker, J. A., & Le Prell, C. G. (2017). Hidden hearing loss? No effect of common recreational noise exposure on cochlear nerve response amplitude in humans. *Frontiers in neuroscience*, *11*, 465.

Grose, J. H., Buss, E., & Hall, J. W. (2017). Loud music exposure and cochlear synaptopathy in young adults: Isolated auditory brainstem response effects but no perceptual consequences. *Trends in hearing*, *21*, 1-18.

Gu, J. W., Herrmann, B. S., Levine, R. A., & Melcher, J. R. (2012). Brainstem auditory evoked potentials suggest a role for the ventral cochlear nucleus in tinnitus. *Journal of the Association for Research in Otolaryngology*, *13*(6), 819-833.

Guest, H., Dewey, R. S., Plack, C. J., Couth, S., Prendergast, G., Bakay, W., & Hall, D. A. (2018). The noise exposure structured interview (NESI): An instrument for the comprehensive estimation of lifetime noise exposure. *Trends in hearing*, *22*.

Guest, H., Munro, K. J., Prendergast, G., Howe, S., & Plack, C. J. (2017). Tinnitus with a normal audiogram: Relation to noise exposure but no evidence for cochlear synaptopathy. *Hearing research*, *344*, 265-274.

Hashimoto, I., Ishiyama, Y., Yoshimoto, T., & Nemoto, S. (1981). Brain-stem auditory-evoked potentials recorded directly from human brain-stem and thalamus. *Brain: a journal of neurology*, *104*(Pt 4), 841-859.

van der Heijden, M., & Trahiotis, C. (1999). Masking with interaurally delayed stimuli: the use of “internal” delays in binaural detection. *The Journal of the Acoustical Society of America*, *105*(1), 388-399.

Hickox, A. E., Larsen, E., Heinz, M. G., Shinobu, L., & Whitton, J. P. (2017). Translational issues in cochlear synaptopathy. *Hearing research*, *349*, 164-171.

Hoben, R., Easow, G., Pevzner, S., & Parker, M. A. (2017). Outer hair cell and auditory nerve function in speech recognition in quiet and in background noise. *Frontiers in neuroscience*, *11*, 157.

Hoover, E., Pasquesi, L., & Souza, P. (2015). Comparison of clinical and traditional gap detection tests. *Journal of the American Academy of Audiology*, *26*(6), 540-546.

Hope, A. J., Luxon, L. M., & Bamiou, D. E. (2013). Effects of chronic noise exposure on speech-in-noise perception in the presence of normal audiometry. *The Journal of laryngology and otology*, *127*(3), 233.

Hox, J. J., van de Schoot, R., & Matthijsse, S. (2012, July). How few countries will do? Comparative survey analysis from a Bayesian perspective. In *Survey Research Methods, 6*(2), 87-93.

Jerger, J., & Musiek, F. (2000). Report of the consensus conference on the diagnosis of auditory processing. *Journal of the American Academy of Audiology*, *11*(9), 467-474.

Johnson, T. A., Cooper, S., Stamper, G. C., & Chertoff, M. (2017). Noise exposure questionnaire: A tool for quantifying annual noise exposure. *Journal of the American Academy of Audiology*, *28*(1), 14-35.

Keith, R.W. (2000). Random Gap Detection Test. Auditec of St Louis Ltd. www.auditec.com

Kidd, G., Mason, C. R., Richards, V. M., Gallun, F. J., & Durlach, N. I. (2008). Informational masking. In Auditory perception of sound sources (p. 143-189). Springer, Boston, MA.

Killion, M. C., Niquette, P. A., Gudmundsen, G. I., Revit, L. J., & Banerjee, S. (2004). Development of a quick speech-in-noise test for measuring signal-to-noise ratio loss in normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America*, *116*(4), 2395-2405.

Kluk, K., Prendergast, G., Guest, H., Munro, K. J., Léger, A., Hall, D. A., ... & Plack, C. J. (2016). No evidence for hidden hearing loss due to noise exposure in young adults with a normal audiogram. *The Journal of the Acoustical Society of America*, *140*(4), 3152-3152.

Kruschke, J. K. (2011). Bayesian assessment of null values via parameter estimation and model comparison. *Perspectives on Psychological Science*, *6*(3), 299-312.

Kruschke, J. K., & Liddell, T. M. (2018). Bayesian data analysis for newcomers. *Psychonomic bulletin & review*, *25*(1), 155-177.

Kumar, U., Ameenudin, S., & Sangamanatha, A. (2012). Temporal and speech processing skills in normal hearing individuals exposed to occupational noise. *Noise and Health*, *14*(58), 100-105.

Kumar, P., Upadhyay, P., Kumar, A., Kumar, S., & Singh, G. B. (2017). Extended high frequency audiometry in users of personal listening devices. *American journal of otolaryngology*, *38*(2), 163-167.

Kujala, T., Shtyrov, Y., Winkler, I., Saher, M., Tervaniemi, M., Sallinen, M., ... & Näätänen, R. (2004). Long-term exposure to noise impairs cortical sound processing and attention control. *Psychophysiology*, *41*(6), 875-881.

Kujawa, S. G., & Liberman, M. C. (2009). Adding insult to injury: cochlear nerve degeneration after "temporary" noise-induced hearing loss. *Journal of Neuroscience*, *29*(45), 14077-14085.

Kujawa, S. G., & Liberman, M. C. (2019). Translating animal models to human therapeutics in noise-induced and age-related hearing loss. *Hearing research*, *377*, 44-52.

Laitinen, H. (2005). Factors affecting the use of hearing protectors among classical music players. *Noise and Health*, *7*(26), 21.

Lee, S. Y., & Song, X. Y. (2004). Evaluation of the Bayesian and maximum likelihood approaches in analyzing structural equation models with small sample sizes. *Multivariate Behavioral Research*, *39*(4), 653-686.

Le Prell, C. G., & Clavier, O. H. (2017). Effects of noise on speech recognition: Challenges for communication by service members. *Hearing Research*, *349*, 76-89.

Le Prell, C. G., Siburt, H. W., Lobarinas, E., Griffiths, S. K., & Spankovich, C. (2018). No reliable association between recreational noise exposure and threshold sensitivity, distortion product otoacoustic emission amplitude, or word-in-noise performance in a college student population. *Ear and hearing*, *39*(6), 1057-1074.

Le Prell, C. G., Spankovich, C., Lobarinas, E., & Griffiths, S. K. (2013). Extended high-frequency thresholds in college students: effects of music player use and other recreational noise. *Journal of the American Academy of Audiology*, *24*(8), 725-739.

Liberman, C. (1982). Acute and chronic effects of acoustic trauma: Cochlear pathology and auditory nerve pathophysiology. *New perspectives on noise-induced hearing loss*, 105-134.

Liberman, M. C. (1988). Physiology of cochlear efferent and afferent neurons: direct comparisons in the same animal. *Hearing research*, *34*(2), 179-191.

Liberman, M. C., Epstein, M. J., Cleveland, S. S., Wang, H., & Maison, S. F. (2016). Toward a differential diagnosis of hidden hearing loss in humans. *PloS One*, *11*(9).

Liberman, M. C., & Kiang, N. Y. (1978). Acoustic trauma in cats: cochlear pathology and auditory-nerve activity. *Acta oto-laryngologica*, *353,* 63.

Liberman, M. C., & Kujawa, S. G. (2017). Cochlear synaptopathy in acquired sensorineural hearing loss: Manifestations and mechanisms. *Hearing research*, *349*, 138-147.

Liberman, L. D., & Liberman, M. C. (2015). Dynamics of cochlear synaptopathy after acoustic overexposure. *Journal of the Association for Research in Otolaryngology*, *16*(2), 205-219.

Liberman, L. D., Suzuki, J., & Liberman, M. C. (2015). Erratum to: Dynamics of cochlear synaptopathy after acoustic overexposure. *Otolaryngology*, *16*(2), 221.

Liberman, L. D., Wang, H., & Liberman, M. C. (2011). Opposing gradients of ribbon size and AMPA receptor expression underlie sensitivity differences among cochlear-nerve/hair-cell synapses. *Journal of Neuroscience*, *31*(3), 801-808.

Lin, H. W., Furman, A. C., Kujawa, S. G., & Liberman, M. C. (2011). Primary neural degeneration in the Guinea pig cochlea after reversible noise-induced threshold shift. *JARO: Journal of the Association for Research in Otolaryngology, 12*(5), 605-616.

Lister, J. J., Roberts, R. A., & Lister, F. L. (2011). An adaptive clinical test of temporal resolution: age effects. *International journal of audiology*, *50*(6), 367-374.

Lopez-Poveda, E. A., & Barrios, P. (2013). A perceptual model of auditory deafferentation. *Proceedings of Meetings on Acoustics ICA2013, 19*(1).

Luce, P.A., Pisoni, D.B. & Goldinger, S.D. 1990. Similarity neighborhoods of spoken words. *Cognitive Models of Speech Processing: Psycholinguistic and Computational Perspectives*. 122-147. Cambridge, MA: MIT Press.

Lüders, D., de Oliveira Gonçalves, C. G., de Lacerda, A. B. M., Regina, S., Schettini, L., da Silva, L. S. G., ... & Marques, J. M. (2016). Hearing and quality of life in musicians of a symphony orchestra. *Audiol Commun Res*, *21, 1-8*.

Madsen, S. M., Marschall, M., Dau, T., & Oxenham, A. J. (2019). Speech perception is similar for musicians and non-musicians across a wide range of conditions. *Scientific reports*, *9*(1), 1-10.

Madsen, S. M., Whiteford, K. L., & Oxenham, A. J. (2017). Musicians do not benefit from differences in fundamental frequency when listening to speech in competing speech backgrounds. *Scientific Reports*, *7*(1), 1-9.

Makary, C. A., Shin, J., Kujawa, S. G., Liberman, M. C., & Merchant, S. N. (2011). Age-related primary cochlear neuronal degeneration in human temporal bones. *Journal of the Association for Research in Otolaryngology*, *12*(6), 711-717.

Mayer, M. L., & Westbrook, G. L. (1987). Permeation and block of N-methyl-D-aspartic acid receptor channels by divalent cations in mouse cultured central neurones. *The Journal of physiology*, *394*(1), 501-527.

McCroskey, R. L., & Keith, R. W. (1996). Auditory fusion test-revised: Instruction and user's manual. *Auditec of St. Louis: St. Louis, MO*.

McElreath, R. (2020). *Statistical rethinking: A Bayesian course with examples in R and Stan*. CRC press.

Mehraei, G., Hickox, A. E., Bharadwaj, H. M., Goldberg, H., Verhulst, S., Liberman, M. C., & Shinn-Cunningham, B. G. (2016). Auditory brainstem response latency in noise as a marker of cochlear synaptopathy. *Journal of Neuroscience*, *36*(13), 3755-3764.

Meyer-Bisch, C. (1996). Epidemiological evaluation of hearing damage related to strongly amplified music (personal cassette players, discotheques, rock concerts)-high-definition audiometric survey on 1364 subjects. *Audiology*, *35*(3), 121-142.

Middlebrooks, J. C., & Green, D. M. (1990). Directional dependence of interaural envelope delays. *The Journal of the Acoustical Society of America*, *87*(5), 2149-2162.

Musacchia, G., Sams, M., Skoe, E., & Kraus, N. (2007). Musicians have enhanced subcortical auditory and audiovisual processing of speech and music. *Proceedings of the National Academy of Sciences*, *104*(40), 15894-15898.

Musacchia, G., Strait, D., & Kraus, N. (2008). Relationships between behavior, brainstem and cortical encoding of seen and heard speech in musicians and non-musicians. *Hearing research*, *241*(1-2), 34-42.

Musiek, F. E., Shinn, J. B., Jirsa, R., Bamiou, D. E., Baran, J. A., & Zaida, E. (2005). GIN (Gaps-In-Noise) test performance in subjects with confirmed central auditory nervous system involvement. *Ear and hearing*, *26*(6), 608-618.

Nilsson, M., Soli, S. D., & Sullivan, J. A. (1994). Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. *The Journal of the Acoustical Society of America*, *95*(2), 1085-1099.

Pantev, C., & Herholz, S. C. (2011). Plasticity of the human auditory cortex related to musical training. *Neuroscience & Biobehavioral Reviews*, *35*(10), 2140-2154.

Parbery-Clark, A., Skoe, E., Lam, C., & Kraus, N. (2009). Musician enhancement for speech-in-noise. *Ear and hearing*, *30*(6), 653-661.

Parbery-Clark, A., Strait, D. L., Anderson, S., Hittner, E., & Kraus, N. (2011). Musical experience and the aging auditory system: implications for cognitive abilities and hearing speech in noise. *PloS one*, *6*(5), e18082.

Patino, C. M., & Ferreira, J. C. (2018). Inclusion and exclusion criteria in research studies: definitions and why they matter. *Jornal Brasileiro de Pneumologia*, *44*(2), 84-84.

Plack, 2014. *The sense of hearing* (2nd ed.). Psychology Pres.

Plack, C. J., Léger, A., Prendergast, G., Kluk, K., Guest, H., & Munro, K. J. (2016). Toward a diagnostic test for hidden hearing loss. *Trends in hearing*, *20*, 1-9.

Plomp, R. (1976). Binaural and monaural speech intelligibility of connected discourse in reverberation as a function of azimuth of a single competing sound source (speech or noise). *Acta Acustica united with Acustica*, *34*(4), 200-211.

Porto, M. A., Gahyva, D. L., Lauris, J. R., & Lopes, A. C. (2004). Audiometric evaluation in extended high frequencies of individuals exposed to occupational noise. *Pro-fono: revista de atualizacao cientifica*, *16*(3), 237-250.

Prendergast, G., Guest, H., Munro, K. J., Kluk, K., Léger, A., Hall, D. A., ... & Plack, C. J. (2017). Effects of noise exposure on young adults with normal audiograms I: Electrophysiology. *Hearing research*, *344*, 68-81.

R Core Team (2017). "R: A language and environment for statistical computing," http://www.R-project.org/ (Last viewed 7/5/2019).

Roberts, R. A., & Lister, J. J. (2004). Effects of age and hearing loss on gap detection and the precedence effect. *Journal of Speech, Language, and Hearing Research, 48,* 482-493.

Robertson, D. (1983). Functional significance of dendritic swelling after loud sounds in the guinea pig cochlea. *Hearing research*, *9*(3), 263-278.

Röer, J. P., Körner, U., Buchner, A., & Bell, R. (2017). Semantic priming by irrelevant speech. *Psychonomic Bulletin & Review*, *24*(4), 1205-1210.

Rudmin, F. (1987). Speech reception thresholds for digits. *The Journal of auditory research*, *27*(1), 15-21.

Ruggles, D. R., Freyman, R. L., & Oxenham, A. J. (2014). Influence of musical training on understanding voiced and whispered speech in noise. *PloS one*, *9*(1), e86980.

Schaette, R., & McAlpine, D. (2011). Tinnitus with a normal audiogram: physiological evidence for hidden hearing loss and computational model. *Journal of Neuroscience*, *31*(38), 13452-13457.

Schneider, P., Scherg, M., Dosch, H. G., Specht, H. J., Gutschalk, A., & Rupp, A. (2002). Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. *Nature neuroscience*, *5*(7), 688-694.

Shehorn, J., Strelcyk, O., & Zahorik, P. (2020). Associations between speech recognition at high levels, the middle ear muscle reflex and noise exposure in individuals with normal audiograms. *Hearing Research*, 392, 1-11.

Shinn-Cunningham, B. G., Schickler, J., Kopčo, N., & Litovsky, R. (2001). Spatial unmasking of nearby speech sources in a simulated anechoic environment. *The Journal of the Acoustical Society of America*, *110*(2), 1118-1129.

Skoe, E., Camera, S., & Tufts, J. (2019). Noise exposure may diminish the musician advantage for perceiving speech in noise. *Ear and hearing*, *40*(4), 782-793.

Soli, S. D., & Wong, L. L. (2008). Assessment of speech intelligibility in noise with the Hearing in Noise Test. *International Journal of Audiology, 47*(6), 356-361.

Spoendlin, H. (1971). Primary structural changes in the organ of Corti after acoustic overstimulation. *Acta oto-laryngologica*, *71*(1-6), 166-176.

Stamper, G. C., & Johnson, T. A. (2015). Auditory function in normal-hearing, noise-exposed human ears. *Ear and hearing*, *36*(2), 172.

Stuermer, K. J., Beutner, D., Foerst, A., Hahn, M., Lang-Roth, R., & Walger, M. (2015). Electrocochleography in children with auditory synaptopathy/neuropathy: diagnostic findings and characteristic parameters. *International journal of pediatric otorhinolaryngology*, *79*(2), 139-145.

Swaminathan, J., Mason, C. R., Streeter, T. M., Best, V., Kidd Jr, G., & Patel, A. D. (2015). Musical training, individual differences and the cocktail party problem. *Scientific reports*, *5*, 1-10.

Tillman, T. W., & Carhart, R. (1966). *An expanded test for speech discrimination utilizing CNC monosyllabic words: Northwestern University Auditory Test No. 6*. Northwestern Univ Evanston Il Auditory Research Lab.

Thompson, E. C., Krizman, J., White-Schwoch, T., Nicol, T., LaBella, C. R., & Kraus, N. (2018). Difficulty hearing in noise: a sequela of concussion in children. *Brain injury*, *32*(6), 763-769.

Trehub, S. E., Schneider, B. A., & Henderson, J. L. (1995). Gap detection in infants, children, and adults. *The Journal of the Acoustical Society of America*, *98*(5), 2532-2541.

Trune, D. R., Mitchell, C., & Phillips, D. S. (1988). The relative importance of head size, gender and age on the auditory brainstem response. *Hearing research*, *32*(2-3), 165-174.

Valderrama, J. T., Beach, E. F., Yeend, I., Sharma, M., Van Dun, B., & Dillon, H. (2018). Effects of lifetime noise exposure on the middle-age human auditory brainstem response, tinnitus and speech-in-noise intelligibility. *Hearing Research*, *365*, 36-48.

Valero, M. D., Burton, J. A., Hauser, S. N., Hackett, T. A., Ramachandran, R., & Liberman, M. C. (2017). Noise-induced cochlear synaptopathy in rhesus monkeys (Macaca mulatta). *Hearing research*, *353*, 213-223.

Verhulst, S., Ernst, F., Garrett, M., & Vasilkov, V. (2018). Suprathreshold psychoacoustics and envelope-following response relations: Normal-hearing, synaptopathy and cochlear gain loss. *Acta Acustica united with Acustica*, *104*(5), 800-803.

Viemeister, N. F. (1979). Temporal modulation transfer functions based upon modulation thresholds. *The Journal of the Acoustical Society of America*, *66*(5), 1364-1380.

Wightman, F., Kistler, D., & Andersen, K. (1994). Reassessment of the role of head movements in human sound localization. *The Journal of the Acoustical Society of America*, *95*(5), 3003-3004

Williams, W., Carter, L., & Seeto, M. (2015). Pure tone hearing thresholds and leisure noise: Is there a relationship? *Noise & health*, *17*(78), 358.

Wilson, R. H., McArdle, R. A., & Smith, S. L. (2007). An evaluation of the BKB-SIN, HINT, QuickSIN, and WIN materials on listeners with normal hearing and listeners with hearing loss. *Journal of Speech, Language, and Hearing Research, 50*(4), 844-856.

Wong, P. C., Skoe, E., Russo, N. M., Dees, T., & Kraus, N. (2007). Musical experience shapes human brainstem encoding of linguistic pitch patterns. *Nature neuroscience*, *10*(4), 420-422.

World Health Organization. (2015). *Hearing loss due to recreational exposure to loud sounds: a review*. https://apps.who.int/iris/handle/10665/154589

Yeend, I., Beach, E. F., Sharma, M., & Dillon, H. (2017). The effects of noise exposure and musical training on suprathreshold auditory processing and speech perception in noise. *Hearing research*, *353*, 224–236.

Yoo, J., & Bidelman, G. M. (2019). Linguistic, perceptual, and cognitive factors underlying musicians' benefits in noise-degraded speech perception. *Hearing research*, *377*, 189-195.

Zadeh, L. M., Silbert, N. H., Sternasty, K., Swanepoel, D. W., Hunter, L. L., & Moore, D. R. (2019). Extended high-frequency hearing enhances speech perception in noise. *Proceedings of the National Academy of Sciences*, *116*(47), 753-759.

Zander, M. F., Spahn, C., & Richter, B. (2008). Employment and acceptance of hearing protectors in classical symphony and opera orchestras. *Noise and Health*, *10*(38), 14-26.

Zendel, B. R., & Alain, C. (2012). Musicians experience less age-related decline in central auditory processing. *Psychology and aging*, *27*(2), 410-417.

van Zuijen, T. L. V., Sussman, E., Winkler, I., Näätänen, R., & Tervaniemi, M. (2004). Grouping of sequential sounds—an event-related potential study comparing musicians and nonmusicians. *Journal of cognitive neuroscience*, *16*(2), 331-338.

Appendices

Appendix A Hidden Hearing Loss Study Protocol – Middle Ear Laboratory

Session 1 (2 hours):

- Consent form
- Tinnitus Handicap Inventory questionnaire
- Otoscopy
- Wideband Acoustic Immittance
- Otoacoustic emissions (TEOAE and DPOAE)
- Multi-frequency tympanometry
- Acoustic reflexes using 500 Hz and broadband noise
- Acoustic reflex latency test using 500 Hz and broadband noise
- Bekesy extended high frequency pure-tone audiometry from 250-16000 Hz
- Bone-conduction audiometry from 500-4000 Hz
- Most comfortable and uncomfortable levels (MCL and UCL) using the rainbow passage
- Loudness scaling at 4kHz
- Masking Level Difference test
- Threshold-in-Noise test
- Multiple Auditory Processing Assessment (35 mins)

Session 2 (1 hour):

- Hearing-in-Noise Test (30 minutes)
- Random Gap Detection Test (10 minutes)
- Temporal Modulation Transfer Function test (10 minutes)
- Digit Triplets Test (10 minutes)

Session 3: (1 hour)

- Noise exposure structured interview (10-20 mins)
- Electrocochleography

Appendix B Raw data

B.1 Raw data obtained for the control group

Participant	NESI (units of noise exposure)	RGDT (msec)	HINT-NF (dB)	HINT-NS (dB)	HINT-ITD (dB)	HINT-ILD (dB)
1	1.1	4	-3.2	-9.1	-10.9	-4.2
2	1.02	4	-3.5	-10.3	-10.5	-3.9
3	0.86	4	-3.1	-6.4	-9.6	-2.8
4	0.035	4	-1.2	-7.8	-5.3	-6.3
5	1.514	4	-1.0	-6.8	-2.7	-5.2
6	0.017	4	-0.9	-10.5	-6.2	-8.3
7	0.219	4	-2.2	-7.0	-4.2	-7.4
8	0.144	4	-1.7	-8.2	-8.3	-5.8
9	0.058	4	-3.1	-12.2	-7.3	-9.0
10	0.092	-	-0.9	-8.3	-6.3	-6.7
11	0.215	-	-1.9	-9.1	-6.8	-4.2
12	1.333	4	-1.9	-9.7	-5.4	-8.6
13	0.559	4	-2.1	-9.3	-5.1	-4.9
14	2.075	4	0.9	-7.0	-6.2	-3.3
15	4.438	4	-1.4	-8.8	-5.0	-8.0
16	7.151	4	-0.8	-7.9	-4.7	-6.4
17	0.04	4	1.0	-8.8	-6.5	-6.2
18	0.052	4	-0.8	-8.3	-7.4	-5.3
19	0.101	4	0.5	-8.0	-3.7	-4.1
20	0.821	4	0.5	-5.7	-4.5	-4.8
21	0.069	-	-2.4	-10.4	-6.8	-6.8
22	6.616	-	0.1	-7.4	-5.4	-8.0

B.2 Raw data obtained for the musician group

Participant	NESI (units of noise exposure)	RGDT (msec)	HINT-NF (dB)	HINT-NS (dB)	HINT-ITD (dB)	HINT-ILD (dB)
23	14.022	4	-2.5	-8.6	-8.6	-4.1
24	14.5	4	0.1	-10.8	-2.1	-4.6
25	138.025	4	-2.1	-5.6	-6.15	-2.95
26	11.997	4	2	-8.25	-8.35	-2.4
27	320.607	4	-2.1	-9.1	-4.3	-6.4
28	0.344	4	-3	-10.55	-6.4	-6.5
29	0.489	2	-1.7	-6.75	-7.7	-4.05
30	20.17	4	-1.7	-10.25	-7	-9.3
31	2.872	2	-2.15	-9.8	-5.6	-7.8
32	2.208	4	-2.05	-10.35	-7.1	-7.55
33	5.835	-	-2.7	-10.3	-6	-7.45
34	2.742	4	-0.95	-9	-6.1	-6.95
35	7.049	4	-1.75	-7.65	-7.7	-7.5
36	0.601	4	-2.15	-8.2	-7.4	-7.4
37	4.602	4	-1.4	-6.8	-5.85	-7.6
38	2.556	4	-2.4	-11.5	-7.8	-7.5
39	4.822	4	-1.8	-10.1	-5.7	-8.7
40	1.483	4	-3.1	-10.55	-5.1	-4.9
41	1.121	4	-3.1	-9.8	-8.2	-8.55
42	3.826	4	-0.95	-9.2	-3	-7

Appendix C Statistical models

C.1 Multilevel regression model with student-t likelihood, log of NESI as the outcome variable, and group as the predictor variable

```
m.NESI.ml <- ulam(
  alist(
    NESI ~ dstudent(nu, mu , sigma ),
    mu <- a[group],
    a[group] ~ dnorm( 0 , sigma_ml),
    sigma <- sig[group],
    sig[group] ~ dexp(1),
    sigma_ml ~ dexp(1 ),
    nu ~ dexp(1)
  ) ,
  data=dlist, chains = 1, cores = 1, warmup = 2000, iter = 10000,
  control = list(adapt_delta=0.95 ))

precis(m.NESI.ml, depth=2)
#          mean    sd    5.5%   94.5%   n_eff   Rhat4
# a[1]     -1.07   0.47  -1.80  -0.31   10270   1
# a[2]     1.52    0.33  1.00   2.05    10239   1
# sig[1]   1.64    0.32  1.18   2.19    8842    1
# sig[2]   1.23    0.30  0.80   1.75    8033    1
# nu       3.34    1.36  1.67   5.82    7357    1
```

C.2 Multilevel regression model with HINT scores as the outcome variable

Selected model: Multilevel regression model with interaction and Student likelihood – non-centered parametrization

```
model.11NC <- ulam(
  alist(
    hint ~ dstudent(5,mu,sigma),
    mu <- a_bar + z[id]*sigma_id + bNG[cond,group],
    a_bar ~ normal(0,1),
    real['4,2']:bNG ~ normal(0,0.35),
    z[id] ~ normal ( 0, 1),
    sigma_id ~ dexp (1),
    sigma ~ dexp (1),

    gq> vector[id]:a <<- a_bar + z*sigma_id #
  ), data=dlist, warmup=30000, iter=60000, chains=1, cores=3,
  control = list(adapt_delta=0.99, max_treedepth = 15), log_lik=TRUE,
  start=list(sigma=sd(dlist$hint))
)

precis(model.11NC, depth=3, pars=c("a_bar", "sigma_id","sigma","bNG"))

#              mean    sd      5.5%    94.5%   n_eff  Rhat4
# a_bar       -0.01    0.18    -0.29    0.28    8441    1
# sigma_id     0.23    0.07     0.12    0.33    6877    1
# sigma        0.41    0.03     0.36    0.46   16253    1
# bNG[1,1]     1.36    0.20     1.05    1.68    9760    1
# bNG[1,2]     1.20    0.20     0.89    1.52    9900    1
# bNG[2,1]    -0.85    0.20    -1.17   -0.54    9798    1
# bNG[2,2]    -1.08    0.20    -1.40   -0.76   10271    1
# bNG[3,1]    -0.09    0.20    -0.42    0.22   10060    1
# bNG[3,2]    -0.20    0.20    -0.53    0.13   10513    1
# bNG[4,1]    -0.08    0.20    -0.41    0.25   10281    1
# bNG[4,2]    -0.29    0.20    -0.62    0.04   10311    1
```

Alternative model: More strongly regularizing prior for bNG parameter (SD = 0.25)

```
model.11NCls <- ulam(
  alist(
    hint ~ dstudent(5,mu,sigma),
    mu <- a_bar + z[id]*sigma_id + bNG[cond,group],
    a_bar ~ normal(0,1),
    real['4,2']:bNG ~ normal(0,0.25),
    z[id] ~ normal ( 0, 1),
```

```
    sigma_id ~ dexp (1),
    sigma ~ dexp (1)

   # gq> vector[id]:a <<- a_bar + z*sigma_id #
  ), data=dlist, warmup=30000, iter=60000, chains=1, cores=3,
  control = list(adapt_delta=0.99, max_treedepth = 15), log_lik=TRUE,
  start=list(sigma=sd(dlist$hint))
)

precis(model.11NCls, depth=3, pars=c("a_bar", "sigma_id","sigma","bNG"))

#              mean     sd     5.5%   94.5%   n_eff Rhat4
# a_bar       -0.01    0.10   -0.17    0.16    8049    1
# sigma_id     0.21    0.07    0.08    0.32    5397    1
# sigma        0.43    0.04    0.38    0.50   11520    1
# bNG[1,1]     1.21    0.13    1.00    1.42   13058    1
# bNG[1,2]     1.08    0.13    0.86    1.28   12064    1
# bNG[2,1]    -0.76    0.13   -0.97   -0.56   12229    1
# bNG[2,2]    -0.93    0.14   -1.15   -0.71   14560    1
# bNG[3,1]    -0.09    0.13   -0.30    0.12   13240    1
# bNG[3,2]    -0.17    0.13   -0.39    0.04   14246    1
# bNG[4,1]    -0.07    0.14   -0.28    0.15   13912    1
# bNG[4,2]    -0.24    0.14   -0.46   -0.02   14795    1
```

Alternative model: More weakly regularizing prior for bNG parameter (SD = 0.75)

```
model.11NCmw <- ulam(
  alist(
    hint ~ dstudent(5,mu,sigma),
    mu <- a_bar + z[id]*sigma_id + bNG[cond,group],
    a_bar ~ normal(0,1),
    real['4,2']:bNG ~ normal(0,0.75),
    z[id] ~ normal ( 0, 1),
    sigma_id ~ dexp (1),
    sigma ~ dexp (1)

    # gq> vector[id]:a <<- a_bar + z*sigma_id #
  ), data=dlist, warmup=30000, iter=60000, chains=1, cores=3,
  control = list(adapt_delta=0.99, max_treedepth = 15), log_lik=TRUE,
  start=list(sigma=sd(dlist$hint))
)
```

```
precis(model.11NCmw, depth=3, pars=c("a_bar", "sigma_id","sigma","bNG"))

#              mean    sd     5.5%   94.5%   n_eff Rhat4
# a_bar       -0.01   0.26  -0.43    0.41     7606   1
# sigma_id     0.23   0.07   0.12    0.33     7229   1
# sigma        0.41   0.03   0.36    0.46    17392   1
# bNG[1,1]     1.40   0.28   0.96    1.84     8147   1
# bNG[1,2]     1.23   0.28   0.80    1.67     8217   1
# bNG[2,1]    -0.87   0.28  -1.31   -0.43     8166   1
# bNG[2,2]    -1.10   0.28  -1.55   -0.66     8314   1
# bNG[3,1]    -0.09   0.28  -0.54    0.35     8415   1
# bNG[3,2]    -0.20   0.28  -0.65    0.25     8380   1
# bNG[4,1]    -0.08   0.28  -0.53    0.37     8396   1
# bNG[4,2]    -0.30   0.28  -0.74    0.15     8502   1
```

Alternative model: Using HalfNormal distribution instead of dexp

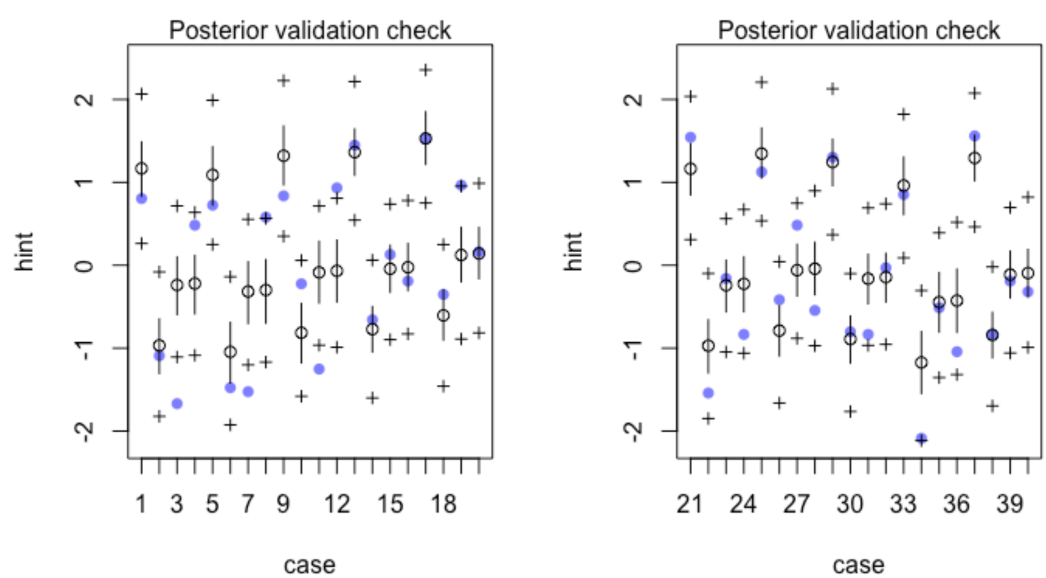
```
model.11NChN <- ulam(
  alist(
    hint ~ dstudent(5,mu,sigma),
    mu <- a_bar + z[id]*sigma_id + bNG[cond,group],
    a_bar ~ normal(0,1),
    real['4,2']:bNG ~ normal(0,0.35),
    z[id] ~ normal ( 0, 1),
    sigma_id ~ dhalfnorm (0,1),
    sigma ~ dhalfnorm (0,1),
        gq> vector[id]:a <<- a_bar + z*sigma_id #
  ), data=dlist, warmup=30000, iter=60000, chains=1, cores=3,
  control = list(adapt_delta=0.99, max_treedepth = 15), log_lik=TRUE,
  start=list(sigma=sd(dlist$hint))

precis(model.11NChN, depth=3, pars=c("a_bar", "sigma_id","sigma","bNG"))

#              mean    sd      5.5%  94.5%   n_eff Rhat4
# a_bar       -0.01   0.14.   -0.22   0.21    6583   1
# sigma_id     0.23   0.07     0.11   0.33    5146   1
# sigma        0.41   0.03     0.36   0.47   13690   1
# bNG[1,1]     1.31   0.16     1.06   1.56    8874   1
# bNG[1,2]     1.16   0.16     0.91   1.41    8536   1
# bNG[2,1]    -0.82   0.16    -1.07  -0.57    8852   1
# bNG[2,2]    -1.02   0.16    -1.28  -0.76    9356   1
# bNG[3,1]    -0.09   0.16    -0.35   0.16    9417   1
# bNG[3,2]    -0.19   0.16    -0.45   0.07    9602   1
# bNG[4,1]    -0.08   0.16    -0.34   0.19    9398   1
# bNG[4,2]    -0.27   0.16    -0.53  -0.01    9355   1
```

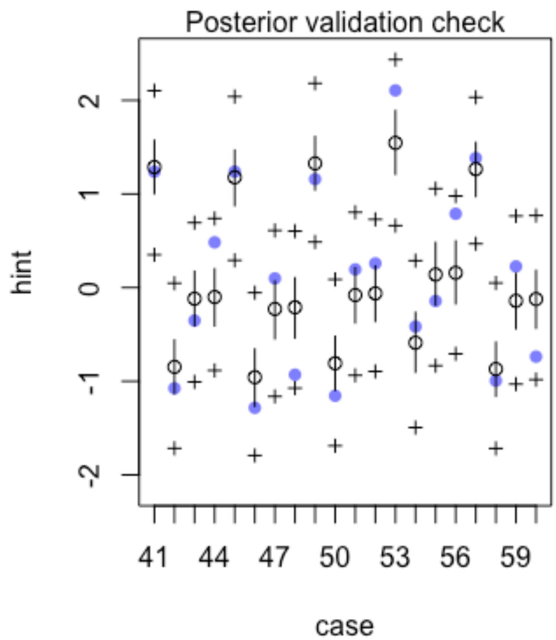
Summary of sensitivity analysis:

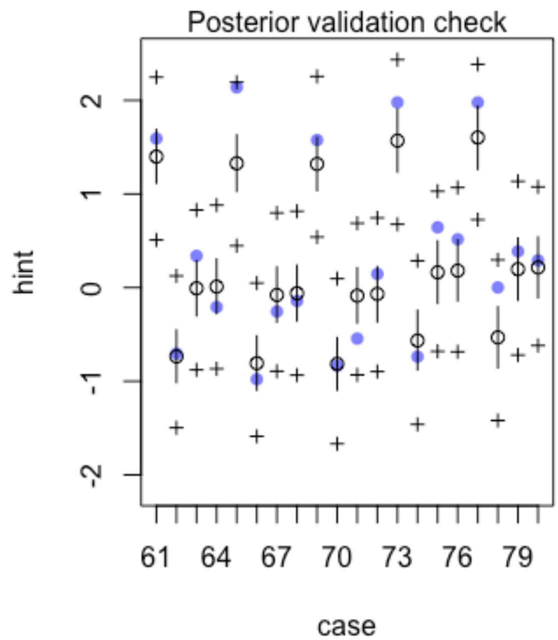
The model using HalfNormal distributions and the model using a less strongly regularizing prior for bNG (SD = 0.75) sample less efficiently than the selected model. The regularization may be too strong when using SD = 0.25 for the interaction coefficient. Using SD = 0.35 for the interaction coefficient leads to more effective sampling.

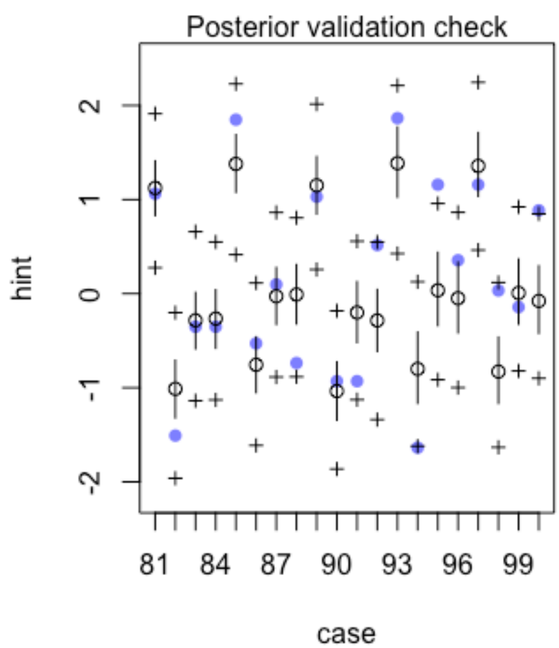
Posterior predictive check for selected model:

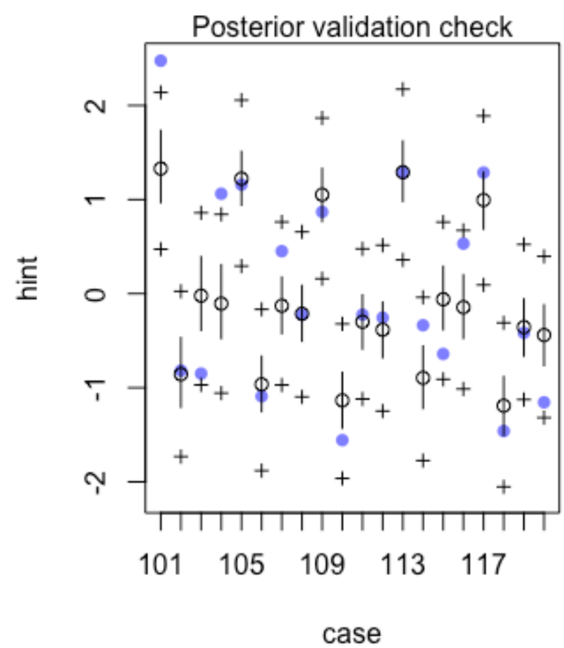
Actual data is represented by the blue dots and predicted data is represented by the open circles. The minimum and maximum values of the collected data are represented by the plus signs. The posterior predictive check shows that prediction is reasonably accurate for most data points. In cases where prediction is less accurate (e.g. cases 3, 100), shrinkage results in worse predictions for some of the more extreme scores.

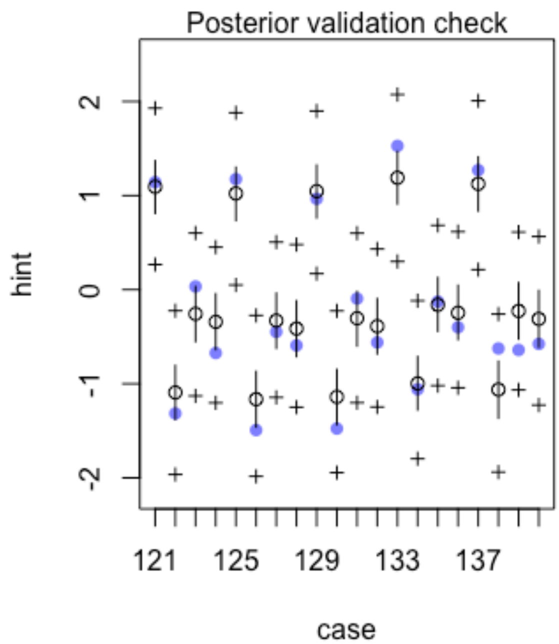


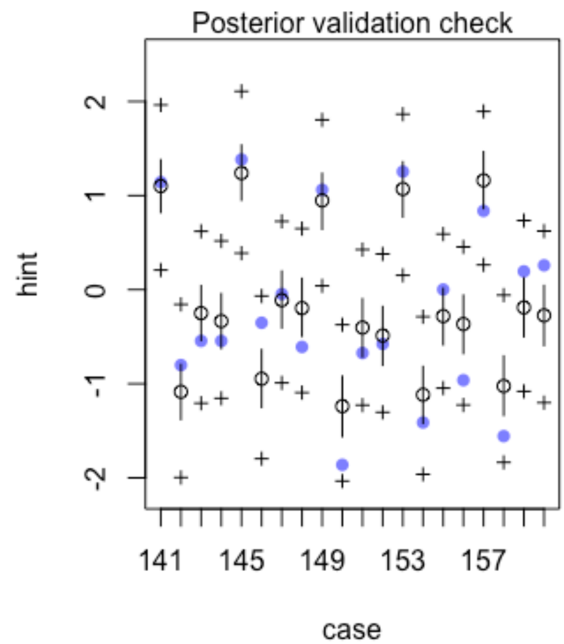

Posterior validation check
hint
2
1
0
-1
-2
41 44 47 50 53 56 59
case

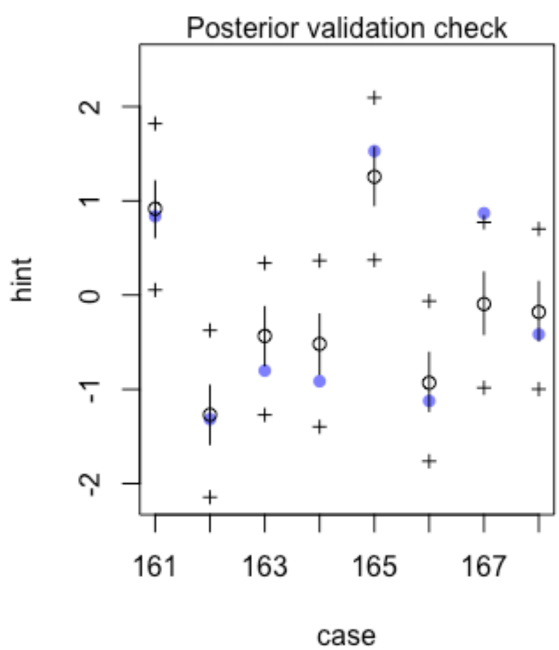

Posterior validation check
hint
2
1
0
-1
-2
61 64 67 70 73 76 79
case


Posterior validation check
hint
2
1
0
-1
-2
81 84 87 90 93 96 99
case


Posterior validation check
hint
2
1
0
-1
-2
101 105 109 113 117
case


Posterior validation check
hint
case
2
1
0
-1
-2
121
125
129
133
137


Posterior validation check
hint
case
2
1
0
-1
-2
141
145
149
153
157


Posterior validation check
hint
case
2
1
0
-1
-2
161
163
165
167

C.3 Regression model with HINT-ITD as the outcome variable and NESI scores as the predictor variable

Selected model: Linear regression with NESI, group, and interaction between group and NESI as predictor variables with strongly regularizing priors (SD = 0.25)

```
mNESIITD.3c <- quap(
  alist(
    ITD ~ dnorm(mu, sigma),
    mu <- a + bN*NESI + bG*Ngroup + bNG*NESI*Ngroup,
    a ~ dnorm (0,0.5),
    bN ~ dnorm (0,0.25),
    bG ~ dnorm (0,0.25),
    bNG ~ dnorm (0,0.25),
    sigma ~ dexp(1)
  ), data = dlist4)

precis(mNESIITD.3c)
#          mean    sd     5.5%   94.5%
# a        -0.05   0.18   -0.34   0.24
# bN       -0.01   0.09   -0.16   0.14
# bG       -0.07   0.21   -0.40   0.26
# bNG       0.11   0.14   -0.11   0.33
# sigma     0.96   0.10    0.80   1.13
```

Alternative model: more weakly regularizing priors for slopes bN, bG and bNG (SD = 1)

```
mNESI.3 <- quap(
  alist(
    ITD ~ dnorm(mu, sigma),
    mu <- a + bN*NESI + bG*Ngroup + bNG*NESI*Ngroup,
    a ~ dnorm (0,0.5),
    bN ~ dnorm (0,1),
    bG ~ dnorm (0,1),
    bNG ~ dnorm (0,1),
    sigma ~ dexp(1)
  ), data = dlist4)

precis(mNESI.3)
#       mean   sd  5.5% 94.5%
#a      -0.03 0.21 -0.36  0.31
# bN    -0.02 0.11 -0.20  0.15
# bG    -0.22 0.35 -0.78  0.34
# bNG    0.17 0.17 -0.09  0.44
# sigma  0.96 0.10  0.79  1.12
```

Alternative model: More strongly regularizing priors for bN, bG and bNG (SD = 0.5)

```
mNESI.3b <- quap(
  alist(
    ITD ~ dnorm(mu, sigma),
    mu <- a + bN*NESI + bG*Ngroup + bNG*NESI*Ngroup,
    a ~ dnorm (0,0.5),
    bN ~ dnorm (0,0.5),
    bG ~ dnorm (0,0.5),
    bNG ~ dnorm (0,0.5),
    sigma ~ dexp(1)
  ), data = dlist4)
precis(mNESI.3b)
#        mean   sd  5.5% 94.5%
# a     -0.04 0.20 -0.36  0.28
# bN    -0.02 0.10 -0.19  0.15
# bG    -0.16 0.30 -0.63  0.32
# bNG    0.15 0.16 -0.10  0.41
# sigma  0.96 0.10  0.80  1.12
```

Summary of sensitivity analysis:

Using less strongly regularizing priors (SD = 0.5 and SD = 1) for bN, bG and bNG lead to unrealistically large SNRs for both groups. The estimates are more precise when using SD = 0.25 as uncertainty intervals are narrower.