Research Article

A Comparison of the Digits-in-Noise Test and Extended High Frequency Response between Formally Trained Musicians and Non-Musicians

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Highlights

- Musician participants do not appear to have a significant advantage for SPIN
- Early signs of music-induced hearing loss were present among the musician group
- SPIN performance was not significantly affected by poorer EHF thresholds

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ABSTRACT

Background and Aim: Musical training has been hypothesised to result in enhanced Speech Perception in Noise (SPIN) abilities, but prolonged exposure to music also increases the risk for Music-Induced Hearing Loss (MIHL). The Signal-to-Noise Ratios (SNR) and the Extended High Frequency (EHF) thresholds between formally trained musicians and non-musicians were compared to determine the effect of musical training on musicians' SPIN and hearing abilities.

Methods: This cross-sectional study included 40 musicians and 39 non-musicians 18–30 years, with mean age (SD) 22.43(2.71) years. EHF audiometry and the Digits-in-Noise (DIN) test were conducted via a smartphone.

Results: Differences found between the two groups regarding the DIN test and EHF thresholds were statistically insignificant. Musicians displayed early signs of MIHL as the musicians reported significantly more ($p=0.004$) instances of tinnitus than non-musicians. A statistically significant correlation was found only for the non-musician group between the 12.5 kHz threshold left and the SNR obtained in the diotic listening condition ($r_s=-0.465$; $p=0.003$).

Conclusion: The results suggested that musicians did not display a significant advantage for SPIN and did not appear to have significantly poorer EHF hearing sensitivity. However, slight trends were noticeable in the musicians which gravitated more towards studies that found enhanced SPIN abilities and elevated EHF thresholds in the musician population. In the future, it may be useful to include additional speech tests (open-set) alongside the DIN test (closed-set). The present study suggests that EHF audiometry may be used for the early detection of MIHL.

Keywords: Music; audiometry; hearing loss; noise-induced; pitch discrimination; sound localization

Introduction

Communication often occurs in noisy environments and, for humans to understand what the speaker is saying, the target speech signal must be separated from the irrelevant signal [1, 2]. This auditory processing ability is called Speech Perception in Noise (SPIN) and it enables people to communicate effectively in many different natural, but unfavourable, listening environments [3]. Top-down influences such as the listener's knowledge of the linguistic structure of the signal as well as his/her ability to use that knowledge to support the process of accurate speech perception will affect the degree to which the listener can accurately detect and recognize speech in background noise [4].

Many studies have suggested that musicians have better SPIN abilities than non-musicians, the so-called "musician advantage for SPIN" [5-9]. There is evidence that individuals who have received musical training from a young age have more robust speech processing abilities, a more vigorous subcortical representation of speech when it is presented in the presence of background noise, and enhanced perception and neural encoding of speech in noise [6, 9]. Furthermore, research suggests that musicians demonstrate enhanced processing abilities and pitch discrimination, especially in the presence of noise [6, 10, 11]. In a study by Strait et al. [9], better Hearing in Noise Test (HINT) scores were obtained from children who received musical training at an early age than from their non-musician peers. Parbery-Clark et al. [7] conducted a study of 31 young adults, of whom 16 participants were acknowledged as musicians. The musicians showed better hearing in noise than the other participants, as they were more sensitive to regularities within a continuous speech stream. Furthermore, Parbery-Clark et al. [6] found that the addition of background noise to speech stimuli had less of an effect on the musicians' auditory brainstem response than in the case of non-musicians. However, several studies did not find a relationship between musical practice and SPIN advantage, with no significant difference between the speech perception abilities of musicians and non-musicians [11-15]. To determine whether such an advantage exists, one would have to consider all factors that may influence the musician's SPIN abilities such as how the duration of exposure to the instrument and type of instrument may alter the central auditory system and higher-level processing, but also how it may affect the peripheral auditory system.

For professional musicians to develop a high level of musical expertise, sufficient amounts of practice are suggested [16]. However, musicians who spend long hours rehearsing and performing are exposed to constant recreational noise. Rock music and classical orchestral music produce sound levels that are often higher than the noise levels allowed by national industry legislation [17]. The National Institute for Occupational Safety and Health (NIOSH) stipulates that noise levels should not exceed 85 dB (A) and should be limited to 85 dB (A) for no longer than eight hours. Emmerich et al. [18] found that the longer the participants in their study were exposed to orchestral music, the lower the amplitudes were of the Distortion Product Otoacoustic Emissions (DPOAEs) measured in these participants. This decline in DPOAE amplitudes suggests that the noise exposure created by instrumental music, may affect hearing sensitivity. The increased risk musicians have for developing hearing loss led to a relatively new term, "Music induced Hearing Loss" (MIHL), that has been coined to describe a condition with characteristics almost identical to those of Noise-Induced Hearing Loss (NIHL) but is caused by music [19, 20].

Similar to noise, music could damage the cochlea's Outer Hair Cells (OHC), possibly resulting in Sensorineural Hearing Loss (SNHL), typically, with a notch at 4 kHz or 6 kHz [20]. The degree of hearing loss a musician may develop will depend on various factors such as the amount of time spent on practicing instrument, the age of the musician, type of instrument played, number of years of exposure to the instrument, and the genre of music produced (rock/classical) [19]. Music-induced SNHL may affect an individual's understanding of speech, especially in the presence of background noise, with SPIN becoming increasingly more difficult with routine exposure to noise and when a hearing loss is present [1, 21]. As the noise usually affects the higher frequencies first (3–8 kHz), MIHL may result in poorer speech intelligibility when frequency components above 3 kHz are used in a conversation, especially when noise is present [22, 23]. Speech perception is particularly affected by the fact that the features of some phonemes necessary to fully understand speech, such as consonant fricatives, are located in the High Frequencies (HF) [24]. Although prolonged music exposure may affect the HFs to some degree, with most prominent frequencies being 2, 3, 4, and 6 kHz, little is known about the effect of music exposure on the Extended High Frequencies (EHFs) (9–20 kHz) [17,18]. It is essential to consider the impact of damaged EHF regions, as important features of SPIN ability are diminished not only by damage in conventional HF regions, but also by damaged EHF regions [23]. Although some studies describe the correlation between the EHFs and SPIN abilities, research has not been specifically focused on the musician population [15, 25]. Some studies have researched the musician population's SPIN abilities in relation to MIHL, however, more emphasis was placed on the conventional HFs than on the EHFs [1, 21]. The limited research available regarding the correlation between specifically the musician population's EHF thresholds and SPIN abilities is surprising, given previous evidence suggesting some correlation between EHF hearing and SPIN abilities [15, 25]. Individuals who have been exposed to noise and who show clinically normal conventional hearing thresholds (0.125 to 8 kHz), but elevated EHF thresholds, may have difficulty perceiving speech [15, 25].

Cochlear Synaptopathy (CS), which is a loss of synapses between cochlear Inner Hair Cells (IHCs), is associated with noise exposure and occurs in the EHF frequency region first, resulting in speech perception difficulties [15, 26, 27]. This phenomenon has been confirmed in many animal studies, but the risk factors for CS in humans still require definement [28]. EHFs play a role in abilities such as SPIN and sound localization [29, 30]. Damage to the EHF regions may, therefore, adversely affect these abilities as elevated EHFs are associated with poorer SPIN abilities [15, 25, 29]. The theory of "hidden hearing loss" suggests that although an individual's conventional audiometry test results may be normal, the individual's ability to hear speech in background noise may be poor and these individuals may also experience tinnitus [31, 32]. Consequently, these individuals' audition may be affected, conventional audiometry seems to show they have threshold within normal limits [31, 32]. There is a higher prevalence of suspected CS in musicians, suggesting EHF involvement [33]. The interest in using EHF audiometry as a tool for hearing conservation programmes to detect changes in hearing sensitivity as early as possible has been rising and the procedure has proven to be especially helpful in the case of individuals younger than 30 years of age [34]. Therefore, using EHF audiometry may be essential for the early detection of OHC damage in young musicians [34, 35].

Considering that noise can damage EHF regions, it seems plausible that music could have the same effect on musicians' EHF hearing. Music and noise are two different entities; however, it has been suggested that both can affect the conventional HFs resulting in similar consequences regarding hearing abilities. Kazkayasi et al. [36] found that young musicians had reduced auditory thresholds at 12, 14, and 16 kHz. De Oliveira Gonçalves et al. [37] reported that musicians had bilateral poorer hearing thresholds at 14 kHz and 16 kHz compared to a non-musician group. Musicians with evidence of noise damage, revealed by a bilateral audiometric notch at 4 or 6 kHz, are at an increased risk of having poorer EHF thresholds [38] and EHF threshold shifts may be an early indicator that an audiometric notch may occur in the future [39]. Contrary to these findings, some studies found no elevated EHF thresholds in musicians and/or no significant differences in the EHF thresholds when musicians were compared to non-musicians [17, 40].

A clear answer regarding the effect of music on the EHF has not been conclusively determined and thus the matter requires further investigation. Furthermore, it is still uncertain how musicians' EHF thresholds and the "musician's advantage" may affect SPIN. When two musicians receive the same significant amounts of musical training, one might show benefits in SPIN, while the other one's EHF region may be more damaged which may, in turn, result in poorer performance on SPIN tasks. In other words, a possible advantage may be diminished due to music-induced damage to the EHF region. This would explain why some musicians show benefits in SPIN and others do not.

The contradictory findings and evidence of previous studies, together with the limitations in research regarding 1) the musician's advantage for SPIN, 2) how music affects EHF hearing, and 3) whether a correlation exists between EHF thresholds and SPIN abilities, call for further investigation into the topic. To provide further evidence on this matter, the following question can be asked: what is the effect of formal music training and the resulting constant exposure to recreational noise on musicians' EHF hearing and, in turn, on their SPIN?

Methods

Participants

This prospective, comparative, cross-sectional study recruited participants from the Department of Music from a South African University. All musician participants underwent or were currently enrolled in a formal music programme. Participants of the control group were recruited from the Faculty of Humanities student body from the same university. A total of 85 participants were recruited, six of whom did not meet the inclusion criteria and were excluded from the study. The final sample comprised of 79 age- and gender-matched young adults (18–30 years, with mean age (SD) 22.43(2.71) years. Forty participants were categorised as musicians, having an experience of at least five years or more of formal musical training and having played a musical instrument consistently for at least three years before participating in the study [41]. The control group consisted of 39 non-musician participants, with 22 who had no history of musical training and 17 who had some form of musical training for less than five years, which took place more than five years before their participation in the study [1]. All participants had intact peripheral auditory systems and normal hearing within the conventional frequency range (0–15 dB at 0.25–8 kHz). Participants reported no history of chronic otitis media, use of ototoxic medication, or traumatic head injuries. Most musician participants (95%, n=38) reported having no occupational noise exposure in addition to their musical activities. Participants from the control group who reported having some occupational noise exposure (5.13%; n=2), such as occasional exposure to loud machinery reported using hearing protection during these exposures. Figure 1 displays the main instrument played by each musician. None of the non-musician participants played instruments (male: n=20, female: n=19). The piano was the most prevalent instrument for the male (n=7) and female (n=10) musician participants. The piccolo and flute were the least prevalent instruments with one female playing the flute and one male playing the piccolo.

Measures

Participants were required to complete a self-administered survey, developed using Qualtrics software, before evaluation. The survey provided the researcher with the relevant case history information regarding each participant's hearing history, musical history, history of noise exposure, instances of tinnitus, and personal perceptions of hearing abilities. The peripheral auditory system of both groups was evaluated using an otoscope (Welch Allyn Pocket LED: REF 901080), a tympanometer (Welch Allyn TM286 AutoTymp), and the hearTest ® application on a smartphone (Samsung Galaxy Trend Neo; Android operating system OS version 4.0.4) together with Sennheiser HDA 300 headphones.

Participants who met the inclusion criteria underwent EHF audiometry and DIN testing within a soundproof booth. All test procedures were conducted in one sitting for each participant. Participants were asked to avoid exposure to loud sounds for 16 hours prior to the evaluation as loud noise can cause a temporary threshold shift, which occurs when there is a shift in the threshold due to noise but the threshold recovers again to baseline after a few hours [42]. EHF smartphone audiometry, as well as the DIN test were conducted using a Samsung Galaxy Trend Neo smartphone, which runs on the Android operating system OS version 4.0.4 (SN: RF8J314CHJP).

For EHF audiometry, the hearTest ® application (HearX group, Pretoria, South Africa) was used to allow for the automated determination of thresholds. The use of the smartphone hearTest application was validated and deemed a reliable tool for determination of EHF thresholds in 2019 [43]. The calibration feature on the hearTest ® application was used for apparatus calibration. Pure tone air-conduction thresholds were obtained for test frequencies 10, 12.5, and 16 kHz (EHF range) using Sennheiser HDA 300 headphones calibrated and adhering to ISO calibration standards (ISO 389-9, 2009). Similar to Bornman et al. [43], the smartphone thresholds seeking algorithm was based on the modified Hughson-Westlake method and was used to obtain pure tone thresholds, with minimum stimulus levels of 0 dB HL across all frequencies and maximum stimulus levels of 60 dB at 10 kHz, 60 dB at 12.5 kHz, and 40 dB at 16 kHz. Smartphone audiometry can either be conducted by means of the participant selecting the response button and testing their hearing with pure tones being presented automatically or by means of the examiner manually presenting the pure tones and, when the participant responds by raising their hand or by saying yes, the examiner presses the response button. The latter technique was used in this study. The examiner was positioned behind the participant to prevent conditioned responses.

For measurement of SPIN abilities, the DIN test was administered by means of the hearDigits ® application which was validated for use in South Africa in 2016 [44]. Three randomised digits (e.g. 3-6-8) were presented binaurally in a steady speech-shaped noise background to determine the participant's SPIN abilities. The aim was to ascertain where 50% of the three-digit combinations could be correctly recognized by the participant [45]. The test stimuli were presented under diotic (digits and masking noise presented interaurally in-phase) and antiphasic (digits 180° inverted to the masking noise; the two signals are spatially segregated) listening conditions using the same Sennheiser HDA 300 headphones that were used for EHF testing [44, 45]. Participants were asked to select a comfortable listening level using a scrollbar, after which several combinations consisting of three random digits, zero to nine, were presented. Participants were required to enter the three digits heard after each combination had been presented. Responses were deemed correct if all three digits were correctly entered [44]. After a response was given, the next digit combination was automatically presented at an increased level (+2 dB) if the response was incorrect or at a decreased level (–2 dB) following a correct response. Order bias was avoided by randomly switching the order in which the antiphasic and diotic test conditions were presented for all participants. The average SNR of the last 19–23 three-digit combinations were used to measure the Speech Reception Threshold (SRT) [44, 45]. A negative SNR (dB) indicates that the presented signal level is lower than the level of the masking noise; consequently, a more negative DIN score indicates better SPIN performance [44, 45]. The Binaural Intelligibility Level Difference (BILD) is the difference in the SNR between the diotic and antiphasic listening conditions and was calculated for all participants after the DIN scores for both conditions had been obtained [46].

Data analysis

Raw data from the Qualtrics survey were exported to the statistical software, Statistical Package for Social Sciences (SPSS) version 28.0 (IBM, 2021) which was used to conduct all statistical analyses. Normality for continuous variables was tested utilizing the Shapiro-Wilk test and it was found to differ significantly from normality and accordingly, non-parametric tests were used instead of parametric tests [47]. Since the underlying distributions of the continuous variables were non-normal, medians (Md) and Interquartile Ranges (IQR) were reported on alongside means (M) and standard deviations (SD). The non-parametric Mann-Whitney U and Spearman correlation coefficients (rs) tests were respectively used to determine statistically significant differences between the two independent groups and to measure the degree of association between the continuous variables [47]. The two-proportions independent samples z-tests were used to determine whether the proportion of responses, in terms of tinnitus perception, differed significantly between the musician group and the non-musician group [47]. For the inferential statistics, effect sizes were computed. For the Mann-Whitney U test, the standardized score (denoted zU) was used and for the two-proportions z test, the statistic itself (zT) was used in the calculation of the effect size with the formulae being that effect size equals z (either zU or zT) divided by the square root of N with N= and and representing the sample sizes of the two groups (musicians and non-musicians) respectively. For correlations, the effect size is easy, as it is equal to the absolute value of the correlation itself. For the current study the recommendations are 0.1, 0.3, and 0.5 for small, medium, and large effect size.

Results

Extended high frequency smartphone audiometry and reports of tinnitus

The Mann-Whitney test was used to determine whether any significant differences were present in the EHF audiometry results between the musicians and non-musicians. The musician group displayed poorer EHF thresholds for all EHFs, except for the 16 kHz right ear threshold, compared to the non-musician group, however, the differences between the musicians' and non-musicians' EHF thresholds were not statistically significant as all the p-values were greater than 0.05 (Table 1). Across all EHFs, the musician participants performed poorer in the left ear, with an average difference between the left and right ear of 1.37 dB. On the other hand, non-musician participants had little to no difference between the left and right ears, with an average difference of 0.56 dB. One possibility for the results not being statistically significant is due to the fact that the effect size ranged from 0.019 to 0.100, which are all classified as very small to small effect sizes. Investigations with very large sample sizes can detect very small differences, however, many researchers have argued that obtaining very large sample sizes to be able to detect very small differences is a meaningless exercise, as larger sample sizes can more easily show significant differences, but the differences may be so small that it has no practical significance [48]. A two-proportions independent samples z-test revealed that musicians reported experiencing tinnitus (80.6%, n=29) significantly more (zT=2.878; p=0.004; effect size=0.324 (medium to large)) than the non-musicians (46.9%, n=15).

Speech perception in noise abilities and digits-in-noise test results

The test scores obtained for the DIN test were compared, and the Mann-Whitney test was used to determine whether any statistically significant differences were present between the musician and non-musician participant groups (Table 2).

For the diotic listening condition, the SNR obtained by the musician group was almost identical to the SNR obtained by the non-musician group with an absolute mean difference of 0.01 and an absolute median difference of 0.2. The SNR obtained in the antiphasic listening condition by the non-musician group was higher than the SNR obtained in the antiphasic condition by the musician group, with the absolute mean and median differences being 0.5 and 0.2 respectively. The BILD was calculated for each group individually to determine the difference between the SNR obtained in the diotic listening condition and the SNR obtained in the antiphasic listening condition. The musician group had a higher BILD than the non-musician group with an absolute mean difference of 0.5 and an absolute median difference of 0.2. In reporting these differences, it is important to note that none of the differences between the musician and non-musician participants (for the diotic and antiphasic listening conditions and BILD) were statistically significant as all the p-values were greater than 0.05 (Table 2). Again, a similar argument

Table 1. Extended high frequency thresholds for the left and right ear

EHF thresholds in dB HL	Ear	Musicians		Non-musicians		Mann-Whitney	p
		Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)		
10 kHz	Right	4.00 (5.57)	0.00 (9.00)	3.72 (5.82)	0.00 (5.00)	734.000	0.610
	Left	5.00 (8.62)	0.00 (5.00)	3.59 (4.99)	0.00 (5.00)	756.500	0.796
12.5 kHz	Right	6.88 (10.11)	5.00 (10.00)	6.28 (9.58)	0.00 (10.00)	733.000	0.618
	Left	8.38 (11.79)	5.00 (14.00)	5.90 (7.94)	5.00 (10.00)	725.000	0.567
16 kHz	Right	13.43 (12.65)	10.00 (20.00)	13.86 (12.13)	15.00 (25.00)	598.000	0.863
	Left	15.00 (12.80)	15.00 (25.00)	12.70 (12.51)	10.00 (25.00)	603.500	0.373

EHF; extended high frequency

Table 2. Digits-in-noise test results for the diotic and antiphasic listening conditions

DIN	Musicians		Non-musicians		Mann-Whitney	p
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)		
Diotic (SNR)	−11.32 (0.76)	−11.20 (1.20)	−11.31 (0.85)	−11.40 (1.20)	773.000	0.945
Antiphasic (SNR)	−19.47 (1.42)	−19.60 (2.00)	−18.96 (1.47)	−19.40 (1.80)	670.500	0.282
BILD (SNR)	8.15 (1.50)	8.00 (1.80)	7.65 (1.35)	7.80 (1.20)	661.000	0.242

DIN; digits-in-noise, IQR; interquartile ranges, SNR; signal-to-noise ratios

holds as in the previous section, in that the effect size range from very small (0.008) to small (0.132), so it is not surprising that the results are not statistically significant.

Correlation between extended high frequency thresholds and digits-in-noise test scores

Non-parametric Spearman correlation coefficients (rs) were used to measure the degree of association between the EHF thresholds and the DIN test results (SNR) of the musicians and non-musicians and is presented in Table 3. Respectively for the musician and non-musician participants, correlations were run for the EHF thresholds at 10, 12.5, and 16 kHz and the SNRs obtained in the diotic and antiphasic listening conditions. Only one correlation was found to be statistically significant and included a negative correlation between the non-musician participants' SNR obtained in the diotic listening condi-

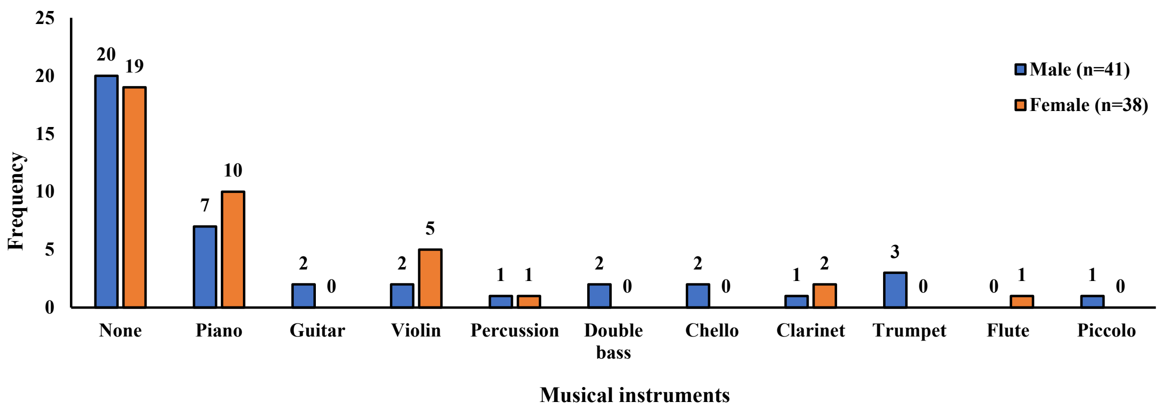

Figure 1. Participant instrument distribution according to gender

Table 3. Correlation between extended high frequencies and digits-in-noise test results of musicians and non-musicians

EHFs		Musicians		Non-musicians	
		DIN diotic listening condition	DIN anti-phasic listening condition	DIN diotic listening condition	DIN anti-phasic listening condition
10 kHz Right ear	rs	–0.103	0.216	0.016	0.006
	p	0.525	0.180	0.923	0.970
10 kHz Left ear	rs	–0.057	–0.033	–0.256	–0.157
	p	0.727	0.840	0.116	0.339
12.5 kHz Right ear	rs	–0.1 40	0.186	–0.072	0.109
	p	0.390	0.250	0.663	0.509
12.5 kHz Left ear	rs	–0.014	–0.120	–0.465	–0.089
	p	0.931	0.462	0.003*	0.590
16 kHz Right ear	rs	–0.238	–0.009	–0.187	–0.104
	p	0.169	0.960	0.281	0.552
16 kHz Left ear	rs	–0.324	0.127	–0.164	–0.058
	p	0.051	0.455	0.331	0.735

EHFs; extended high frequencies, DIN; digits-in-noise

* $p<0.05$

tion and the EHF 12.5 kHz for the left ear only (rs=–465; p=0.003; effect size=0.465 (the largest effect size of all the correlations)). This suggests that as the 12.5 kHz threshold (dB HL) increased (became more elevated) the non-musicians' SNR decreased. This was, however, the only significant correlation that was present and it was only for the non-musician group. Therefore, it is safe to say that the EHF thresholds obtained by the musician participants did not have a significant influence on their SPIN abilities.

Discussion

This study compared the EHF hearing thresholds, and the DIN test scores (SNR) in normal-hearing musicians and non-musicians. The data revealed no statistically significant group difference for the EHF smartphone audiometry and DIN test results.

The musician versus the non-musician speech perception in noise abilities

Previous research has suggested that musicians have enhanced SPIN abilities [6, 7, 10, 11]. The current study results, however, do not correlate with those of previous studies that indicated a significant musician advantage for SPIN [5-10], but do concur with studies that found small, but insignificant, differences between the SPIN performance of musician participants and non-musician participants [11-15]. The DIN test used in the current study subjectively measured the SPIN performance of musicians and non-musicians. On the other hand, Parbery-Clark et al. [49] found that adult musician participants outperformed non-musician participants on SPIN tasks for signals that were not spatially segregated, which is considered to be a more challenging perceptual task than when signals are spatially segregated [50]. The group differences found in the current study were more similar to the differences reported by Strait et al. [9], with a more pronounced difference found between musician and non-musician participants for SPIN tasks where the signals were spatially segregated, as determined by the antiphasic listening condition of the DIN test. However, in the current study these group differences were not statistically significant. Also, the results obtained by Strait et al. [9] were based on the performance of children (7 to 13 years old) and not adults. Strait et al. [9] suggested that enhancements in perception may start to appear at this easier level first (spatially segregated), and may progress to more advanced levels, as SPIN may be developed faster in children who started musical training at a young age. In this study the starting age of musical training was not part of the inclusion criteria. It is possible, therefore, that the musicians' performance in the present study may be different from the performance of other musicians if their musical training started later in life. Musical training may not be the only factor that can contribute to the improved speech task performances observed in primarily professional musicians, but also in those populations receiving musical training but who are not considered to be professional musicians. Innate characteristics, such as above average auditory skills, may be a required skill for becoming a successful musician [51]. This suggests two possibilities. Either the slightly better SNRs obtained by musicians in the antiphasic condition reflect slight trends of enhanced brain plasticity, or the musician participants may have a small genetic advantage in the ability to detect the subtle acoustic discrepancies compared to their non-musician counterparts. It is important to note that longitudinal studies are recommended to determine whether a musician advantage for SPIN is due to pre-existing group differences or musical training [52, 53]. In a longitudinal study, Slater et al. [2] collected data over a span of three years from two groups of participants. By the third-year group one completed one year of musical training and group two completed two full years of musical training. They found that group two had improved SPIN abilities compared to group one who had less musical training, validating the presence of a relationship between SPIN abilities and years of musical training and suggesting that previous studies, like the current one, should perhaps not attribute any musician advantage for SPIN to merely genetic predispositions and pre-existing group differences [2] . Hennessey et al. [52] findings concur previous longitudinal studies that suggested musical training may strengthen SPIN. However, they suggest that the effects of pre-existing group differences on SPIN, such as genetics, and the effects of musical training on SPIN should be separated. They report that the only plausible way for this separation is to conduct a meta-analysis of longitudinal studies.

Both the musicians and non-musicians performed better in the antiphasic listening condition than the diotic listening condition. This finding agrees with those of De Sousa et al. [45], who reported that the ability to detect speech in noise typically improved when a diotic masking signal was used with a 180° phase inverted target signal. This phenomenon is also referred to as binaural unmasking [54, 55]. A phase-inverted stimulus is more easily recognized in the brainstem, resulting in a better SNR [50, 56]. Therefore, based on previous studies suggesting that musicians may have improved control over the descending auditory pathway and increased neuroplasticity, which may include plasticity of the auditory brainstem, due to extensive musical training, it was expected that the musician participants in the current study would obtain significantly higher BILD scores [1, 9, 57]. In reality, a slight but insignificant difference was found regarding the musician and non-musician BILD, with musicians having a slightly higher BILD mean value compared to the non-musicians. Although this finding suggests that that the effect of binaural unmasking was slightly better in the musician participants and that musician participants showed small trends of improved SPIN abilities by being marginally better at processing speech in noise and having somewhat finer spatial segregation of speech abilities, they did not appear to be at a distinct advantage for SPIN compared to the non-musician participants. It is, therefore, possible that the functional benefits musical training may yield do not necessarily generalise to the specific regions evaluated by the DIN test.

The DIN test used in the current study subjectively measured the SPIN performance of musicians and non-musicians. Therefore, on the basis of subjectivity the musicians did not seem to perform significantly better on SPIN tasks. However, studies that used objective measures such as Functional Magnetic Response Imaging (fMRI) and Auditory Brainstem Responses (ABR) found evidence of some musician advantage for SPIN. Delays in the timing of the ABR can occur when background noise is added, however, these delays in timing seemed to be smaller in musicians than non-musicians [6]. Additionally, Du and Zatorre [58] determined SPIN abilities of musicians and non-musicians using English phonemes tokens presented in broadband noise. Stronger activation of cortical regions associated with speech processing and production, including Broca's area in the left inferior frontal gyrus and right auditory regions, were noted in musicians [58]. It should, therefore, be noted that digits alone may not be a true representation of SPIN relative to more complex speech stimuli. The triplet combinations (zero to nine) used in the DIN test allow nine possible items to be recognized. Therefore, using digits as the main speech stimulus will provide a relatively closed-set speech task [59]. On the other hand, speech stimuli such as words and sentences will allow for a more open-set speech task, resulting in a more challenging task and possibly resulting in a different SNR than when digits are used [59]. McArdle et al. [59] found a SNR difference of 16–17 dB when digits were used compared to when words were used, both presented in multi-talker babble. Therefore, the stimulus type as well as the objectivity of a test can significantly affect the results obtained from SPIN tasks and it is recommended for future research to include a combination of subjective and objective measures which includes open- and closed-set tasks by utilising additional speech tests alongside the DIN test.

Ruggles et al. [11] reported that, at least for the younger adult population in their study, the enhanced processing abilities fuelled by musical training may not necessarily generalize to the SPIN domain. Parbery-Clark et al. suggested that the results of the HINT and QuickSIN tests did not correlate. Therefore, they suggested that although both tests were measures of SPIN abilities, different aspects of SPIN were measured by each test [49]. The findings of Ruggles et al. [11] and Parbery-Clark et al. [49] suggest that musical training may be beneficial and cause better performance only for some areas of speech perception, such as pitch, acoustic regularities, rhythm, timbre, etc. or only enhance some functions such as auditory attention or auditory working memory, and not necessarily improve SPIN as a whole. It should also be pointed out that many of the previous studies which found evidence of an advantage and suggested musical training as a therapy tool for improving SPIN, only included musicians who started training before age seven [5-7, 9, 11] and who had been playing the instrument consistently for at least ten years [5-7, 11]. In contrast, the current study included musicians with a minimum requirement of five years of professional training and who had been playing the instrument consistently for at least three years. The presence of an advantage may depend on the degree and amount of training a musician has received. The amount of exposure and training required for benefits to occur, therefore, requires further investigation before the assumption can be made that musical training will provide any particular benefits within the speech domain, including general speech understanding and SPIN, and especially before deciding whether musical training can be a successful aid for children with language impairment [6, 60] and/or a rehabilitation tool for individuals with cochlear implants [5].

The extended high frequency thresholds and tinnitus

Musicians rely heavily on their hearing abilities to accurately segregate musical tones and to separate and/-or combine different frequencies across a broad range [19]. Without excellent hearing, the average musician would likely struggle to engage in the practice of an instrument or performance within an orchestra. However, musicians are exposed to noise more often than most other people and are at an increased risk of developing MIHL as well as experiencing tinnitus [61-63]. This was supported by the current study, as the musicians reported instances of tinnitus significantly more than their age- and gender-matched non-musician counterparts. Schmidt et al. [63] found that the tinnitus experienced by musicians may be related to their lifetime exposure to music. Additionally, Burns-O'Connel et al. [62] found that musicians reported tinnitus to be a significant problem in their lives and Couth et al. [35] found that musicians were more likely to experience tinnitus. These results from previous studies, together with the results from the current study, suggest that tinnitus may be a common problem among the musician population.

Previous findings indicated that occupational and recreational noise exposure may damage the EHF regions [26, 64, 65]. Based on these findings it was expected that musician participants in the present study would have significantly worse EHF thresholds compared to the non-musician participants. However, the current data revealed no evidence that the musician participants' EHF hearing sensitivity was significantly worse than that of the non-musician participants. Zhang et al. [40] also found that their musician participants had slightly poorer EHF thresholds than the non-musician participants, but the differences were not statistically significant. In view of the musician participants' normal conventional pure tone thresholds and no significant elevation of EHF thresholds or diminished SPIN, the current study cannot report any evidence of "hidden hearing loss". It is also important to distinguish OHC loss from IHC loss before any inferences can be made regarding CS and the current study did not utilize tests such as electrocochleography for the detection of damage to the cochlear IHCs or otoacoustic emissions for the detection of OHC damage [28, 66].

Interestingly, across all EHFs the musicians' left ear thresholds were poorer compared to their right ear thresholds. In contrast, non-musicians had little or no difference between the left and right ears. Many studies have also described this "left ear" trend, and some suggest this may be due to the positioning of instruments as some instruments, especially string instruments, are positioned on the left side of the body and sounds are therefore in closer proximity to the left ear [63, 67-69]. The current study was not instrument specific and it is, therefore, unknown whether the "left ear trend" noticeable in the musician group was more prevalent among string instrumentalists as indicated by previous studies [63, 67-69]. To make this distinction one would have to separately measure the sound levels produced by the instrument at each participant's ear [69]. The musician positioning within the orchestra should also be considered as some musicians will be exposed to several other instruments, in addition to their own, from many different angles, depending on where they are placed. The present results do not preclude EHF threshold differences later in life as these differences may increase over time. EHF thresholds may change due to the type of instrument played, more significant duration of exposure, whether Hearing Protection Devices (HPD) were used over time, and age of the musicians. The slightly poorer EHF thresholds obtained by musician participants, together with the group difference regarding left and right ear differences, which indicated that those who were exposed to instruments were more likely to have poorer hearing thresholds in the left ear, as well as the significantly higher prevalence of tinnitus, suggests that musicians are at an increased risk for developing MIHL at a later stage. Therefore, this study suggests that EHF audiometry may be a valuable tool to monitor the musicians' hearing for early detection and prevention of MIHL. With the correct use of adequate HPDs together with early detection of changes in auditory functioning, the musicians' hearing may be preserved.

Correlation between extended high frequencies and speech perception in noise abilities

The correlation between hearing at EHFs and the SPIN of musicians compared to non-musicians has not been researched to any great extent. Previous research either investigated the correlation between the EHF thresholds and SPIN abilities but did not focus particularly on the musician population [15, 25], or they investigated a musician population but did not specify the EHF region [1]. Therefore, the current study aimed to determine whether a correlation existed between the EHF thresholds and SPIN abilities of a group of musician participants and to compare the results to those obtained from a group of non-musician participants. EHFs contribute to accurate SPIN and localization of sound sources, and music-induced damage to EHF regions may adversely affect these abilities [29, 30].

Overall, the significance of the correlations found in both groups were minimal and not statistically significant. The only significant correlation difference was found between the left ear SNR (diotic condition) and the 12.5 kHz EHF threshold of the non-musician group compared to the results of the musician participant group. In other words, the current study did not find evidence that poorer EHF thresholds resulted in poorer performance in the DIN test and vice versa in the musician participants. Motlagh Zadeh et al., confirmed a relationship between EHF hearing and SPIN abilities by utilizing the DIN test. They did, however, point out that the SRTs of participants with and without hearing loss in the EHF range improved particularly when supplementary EHF energy (energy above 8 kHz) in the DIN task was provided [70]. In a study similar to the current study, Mishra et al. [25] measured the EHFs and SRT's of 222 young adults using single digits within the presence of multi-talker babble noise, and reported that elevated EHF thresholds might have a degradative effect on SPIN abilities. Likewise, Yeend et al. [15] found that participants with elevated EHF thresholds performed more poorly on SPIN tasks. However, the participants in the study by Mishra et al. [25] were not classified as musicians and the participants in the study of Yeend et al. [15] consisted of 17% of participants working as professional musicians and 40% who had substantial musical training. Therefore, the relationship between EHF thresholds and SPIN described by these studies may not apply strictly to the musician population. Parbery-Clark et al. [1] compared middle-aged musicians to age- and hearing-matched non-musicians and found that, even with hearing loss, musicians still performed better in SPIN tasks (HINT) than non-musicians, but it was not specified whether the hearing loss was exclusively in the EHFs. Further research in this regard is warranted to determine how EHF thresholds and SPIN abilities influence one another, specifically in the musician population.

Due to the small, insignificant differences between the musician and non-musician participants, with the only significant difference found being for reports of tinnitus, a general assumption cannot be made that musicians have a significant advantage for SPIN or that musicians' EHFs will be significantly more elevated compared to that of non-musicians. However, there were slight trends noticeable in the musician participants which gravitated more towards studies that found enhancements in SPIN and elevated EHF thresholds in the musician population [5-10, 36, 37, 40]. There is compelling evidence suggesting a correlation between years of musical training and auditory neural enhancements, with more years of musical training being associated with improved SPIN and improved working memory [6, 9, 49, 57, 71]. Additionally, studies have indicated that auditory thresholds may become increasingly worse as the years of musical exposure increase, especially in the EHF region [37, 72]. This suggests that there is a potential for group differences to change over time as years of musical exposure increase, such as deterioration of the EHF thresholds and possible advancements in the performance of SPIN.

Limitations and future directions

McKay [53] suggested that when differences are noted between musicians and non-musicians regarding their SPIN abilities, longitudinal studies should be used to distinguish whether these differences were mediated by the musical training itself or by genetic factors and predetermined talents. It is, therefore, recommended that future research should use a longitudinal study that considers factors such as developmental history, cultural background and upbringing, as well as genetics, as this may yield more accurate results regarding the degree to which solely musical training influences SPIN abilities.

The amount of exposure and training required for benefits in speech perception needs further investigation before the assumption can be made that musical training could or could not provide any specific enhancements in speech-related tasks and abilities, including SPIN. More information is also needed regarding the degree and duration of exposure to music (recreational noise) for significant EHF threshold shifts to occur. Therefore, future research should use a larger sample size including samples of musicians with various durations of exposure to musical training (e.g. five years, seven years, ten years, 20 years). The EHF thresholds and SPIN abilities for each of these groups should be assessed, and the results compared. Each group should, however, also have age- and gender-matched controls. This will clarify whether the results obtained are associated with the length of exposure and whether responses may change over time.

Some instruments may have a more significant effect on hearing and SPIN than others. Therefore, it may be beneficial for future research to determine the effect of specific instruments on hearing sensitivity, specifically in the EHF region, and SPIN in musicians.

Conclusion

The current study results did not indicate a significant musician advantage for Speech Perception in Noise

(SPIN) but do not rule out the possibility that the musicians may have some potential to develop an advantage for SPIN in the future. For the future, it may be useful to conduct a battery of tests which includes objective and subjective measures of SPIN performance as well as open-set speech stimuli alongside the digits-in-noise

test (closed-set stimulus). The musician participants showed early signs of Music-Induced Hearing Loss (MIHL) as indicated by their Extended High Frequency (EHF) results and reports of tinnitus and EHF audiometry may, therefore, be utilized for the early detection of MIHL in the young musician. However, the neural resilience musicians are displaying together with the evidence of benefits produced by musical training, which may enrich the academic success in children, calls for further research on this topic. Research should also consider all the risks involved with musical training, such as possible MIHL, when investigating the benefits musical training may yield.

Ethical Considerations

Compliance with ethical guidelines

This study was reviewed and received ethical approval from the Survey Committee and from the Faculty of Humanities Research Ethics Committee, University of Pretoria (reference number: HUM050/0621). The Declarations of Helsinki and Tokyo for human research have been adhered to. All participants were informed of the research aims and procedures and voluntarily provided written consent prior to the commencement of procedures.

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Authors' contributions

BD: Study design, data collection, interpretation of the results, and writing the manuscript; LP and MS: Study concept, and design, supervision, and final revision; MAG: Statistical analysis, supervision, and interpretation of results.

Conflict of interest

There are no competing financial interests.

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