Music Perception in Older Adults With Hearing Loss: Protective Effect of Musical Experience

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Objectives: The goal of this project was to investigate the impact of musical experience, hearing loss, and age on music perception in older adults. The authors hypothesized that older adults with a varying degree of musical experience would perform better at music perception tasks than their counterparts without musical experience while controlling for age and hearing loss.

Design: This study used a descriptive correlational cross-sectional design. Seventy-seven older adults aged 60 to 90 years were recruited and divided into two groups based on their lifetime musical experience: the group without musical experience (n = 39) and the *M* group (with musical experience; n = 38). Participants in the *M* group had either played an instrument for 5 years or more and/or taken at least 1 year of music lessons. Following a hearing screening and a musical experience questionnaire, participants completed two music perception tasks: (1) a short version of the Montreal Battery Evaluation of Amusia (MBEA) measuring melodic (scale and contour) and rhythm perception, and (2) an instrument discrimination task measuring timbre perception.

Results: Results revealed that participants of the *M* group had a significantly higher accuracy in both tasks compared with the group without musical experience while controlling for age and hearing loss. Moreover, a significant interaction was found between group effect and hearing loss for the MBEA, suggesting that musical experience moderates the impact of hearing loss on melodic and rhythm perception abilities. Finally, the amount of musical experience was the most important positive predictor for MBEA accuracy in the *M* group.

Conclusions: These results suggest that despite age-related hearing loss, older adults with musical experience still benefit from their experience-driven enhancement in melodic, rhythm, and timbre perception. Findings from this study support the notion that music training is beneficial for music perception abilities, providing protection against the impact of presbycusis.

Key words: Age-related hearing loss, Central auditory abilities, Music perception, Musical experience.

Abbreviations:GAI = Geriatric Anxiety Inventory; GDS = Geriatric Depression Scale; *M* = group with musical experience; MBEA = Montreal Battery Evaluation of Amusia; MoCA = Montreal Cognitive Assessment; NM = group without musical experience; PTA = pure-tone average; PTA_{HF} = pure-tone average for high frequencies (3, 4, 6, 8 kHz).

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INTRODUCTION

Music is one of the oldest art forms known to humanity (Wallin et al. 1999). As a universal phenomenon transcending eras and cultures, it remains one of the greatest sources of pleasure in human experience (Fung & Lehmberg 2016). Several studies have shown the positive effects of music on well-being across the lifespan in a wide variety of contexts (Croom 2015; Welch et al. 2020; Dingle et al. 2021; Granot et al. 2021). Amongst older adults, musical activities such as listening to music and playing music have been reported to improve their overall quality of life, contributing to their psychological well-being (Coffman 2002; Hays et al 2002; Laukka 2007; Solé et al 2010; MacDonald 2013; Fung & Lehmberg 2016). However, to appreciate music and benefit from it, the auditory system must be able to perceive and analyze temporally and spectrally complex auditory stimuli. This represents a challenge in the presence of age-related changes in sensory processing.

Presbycusis, or age-related hearing loss, is one of the most prevalent chronic health conditions among older adults. According to the World Health Organization, it affects approximately 65% of the world's population over 60 years old (World Health Organization 2021). Presbycusis refers to the age-related degradation of structures in the middle ear, inner ear, and central auditory pathways which leads to a progressive deterioration of auditory functions (Gates & Mills 2005; Yamasoba et al. 2013). Because many parts of the globe are experiencing population aging (Lv et al. 2023), the number of older adults with hearing loss is expected to increase significantly in the coming years. People with hearing loss face numerous obstacles related to sound perception (Moore 1996, 2007) which can decrease music enjoyment in comparison to normal-hearing individuals (Leek et al. 2008; Looi et al. 2019; Greasley et al. 2020; Chern et al. 2023).

Several studies have reported that presbycusis impacts music perception. Using the Montreal Battery Evaluation of Amusia (MBEA), a standardized test measuring music perception disorders, Moreno-Gómez et al. (2017) reported that presbycusis impairs important music perception abilities such as melodic (scale, contour, and interval) and temporal (rhythm and meter) perception. Hake et al. (2023) developed a Musical Scene Analysis task to explore if hearing loss affects auditory abilities in realistic music scenarios. Participants had to detect a single target instrument in an excerpt with multiple instruments. Results revealed that the degree of hearing loss was negatively associated with accuracy in this task. Moreover, studies reported that alterations to music perception also occur in older individuals without hearing loss. Clinard et al. (2010) observed that older normal-hearing individuals experience a significant decline in frequency discrimination abilities, while Bones and Plack (2015) revealed

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a lower musical harmony perception within the same population. However, generalization of these results is limited. Most hearing screening protocols used in previous studies did not measure frequencies above 4 kHz, where presbycusis is most likely to occur (Gates & Mills 2005; International Organization for Standardization 2017). This may result in overlooking high-frequency hearing loss and categorizing participants as having normal-hearing thresholds, despite potential hearing loss-related difficulties in music perception. Moreover, very few studies quantify older adults' musical experience, often relying solely on a dichotomous variable (with or without musical experience) to assess its impact on auditory abilities, thus limiting conclusions about the relation between musical experience and music perception abilities in this population.

Numerous studies have indeed reported that extensive musical training started at an early age and lifelong musical experience both lead to positive effects on several central auditory processing abilities which persist even at an advanced age (Zendel & Alain 2012; Grassi et al. 2017; Maillard et al. 2023). According to Zendel and Alain (2012), musicians experience less age-related decline in gap-detection and speech-in-noise thresholds compared with nonmusicians. Older musicians perform better than age-matched nonmusicians in frequency discrimination, duration discrimination, and gap-detection tasks (Grassi et al. 2017). Likewise, an increasing number of studies are reporting a robust positive association between musicianship and speech-in-noise perception for older people (Parbery-Clark et al. 2011; Coffey et al. 2017; Zendel et al. 2019; Zhang et al. 2021; Maillard et al. 2023). However, these studies are limited by excluding individuals with hearing loss, which represents a significant proportion of the older population because of the high prevalence of presbycusis.

Due to its numerous benefits on auditory abilities, there has been a growing interest in exploring the use of music as a rehabilitation tool for people with hearing loss. A recent literature review highlighted how musical intervention, even if started at an advanced age, may be beneficial for improving auditory abilities such as pitch perception and speech-in-noise processing in older adults (Grenier et al. 2021). However, the studies included in this review present the same limitations regarding audiological and musical experience assessment, making it difficult to clearly demonstrate the link between age, hearing loss, and musical experience on music perception skills.

All in all, although research shows that presbycusis and aging impair music perception abilities whereas musical training enhances these auditory skills, there remains a gap in the literature concerning how musical experience influences music perception in older adults with age-related hearing loss. This is at least in part due to methodological limitations in existing studies, such as incomplete assessment of auditory thresholds (not covering the full frequency range) and a lack of quantification of musical experience. Therefore, the primary aim of this study was to compare performance in music perception tasks between older adults with and without musical experience while controlling for the effect of age and hearing loss. A secondary objective was to investigate how age, hearing loss, and the amount of musical experience predict accuracy in these tasks in older adults with musical experience.

MATERIALS AND METHODS

Participants

Recruitment and Screening • Ninety-three older adults were initially recruited. A convenience sampling was chosen to reach as many people as possible. Recruitment was carried out using a poster which was distributed by email to the community of Laval University as well as various health and community organizations across Quebec City. Our team also presented the project in several residences for older adults. A screening interview was conducted over the phone to retrieve sociodemographic data such as age, gender, and education level. Exclusion criteria were severe osteoarthritis and significant vision problems, which were self-reported during the interview. To avoid possible confounding variables, exclusion criteria also included the presence of psychological and neurodegenerative disorders. Anxiety symptoms were screened in person at CERVO Brain Research using the Geriatric Anxiety Inventory (GAI), a 20-item questionnaire with a cutoff score of 10 (Champagne et al. 2018). Depression symptoms were screened with the 30-item version of the Geriatric Depression Scale (GDS), with a cutoff score at 11, suggesting a mild depression (Bourque et al. 1990). The Montreal Cognitive Assessment (MoCA) (Nasreddine et al. 2005), a 30-item cognitive screening tool was used to measure general cognitive functioning. It has been reported that the original cutoff score of 26 increases the risk of false positive (Carson et al. 2018). Considering this limitation, we used the regression-based norms for French-speaking middle-aged and older adults people from Quebec (Larouche et al. 2016). These norms, adjusted for age, education, and sex, maximize specificity and sensitivity and thus enable a better screening. Fifteen individuals were excluded based on their results. Seven individuals were excluded based on their MoCA score, 1 was excluded based on its GDS score (score = 14), 1 was excluded based on its GAI score (score = 11) and 2 were excluded based on their GDS (>11) and GAI (>10) score. Finally, 5 individuals did not attend their scheduled testing sessions at the research center and subsequently dropped out from the project. Ultimately, data from 77 older adults (44F, 60 to 90 years, $M = 71$, SD = 8) were included in this study. Participants' characteristics are presented in Table 1. All participants were in good overall health and had no known history of psychiatric disorders. Independent t tests revealed no significant differences between groups for age, MoCA, GDS, and GAI scores. However, a significant difference between groups was found relative to hearing thresholds (pure-tone average [PTA] at 0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz), $t(75) = 2.746$, $p = 0.008$ with the musical experience (M) group having a significantly lower PTA score ($M = 44.5$, SD = 22.0) than the group without musical experience (NM; $M = 58.3$, SD = 21.9) (Table 1). Moreover, chi-squared tests revealed significant differences between groups for level of education, $\chi^2(2) = 7.13$, $p = 0.028$, and use of hearing aids $\chi^2(1) = 9.52$, $p = 0.002$, but not sex (Table 1). Given the significant differences observed between groups for these participant characteristics variables, they were included in the main analysis to explore their potential impact on the main dependent variables of interest. These are reported in the Results. The study was approved by the institutional review board. Written and informed consent was given by all test subjects before inclusion in the study.

Musical Experience Characterization • Musical experience was assessed using selected items from the Edinburgh Lifetime

Musical Experience Questionnaire which include 30 items divided into four sections: (1) musical instruments, (2) singing, (3) reading music, and (4) listening to music (Okely et al. 2021). Only questions about musical training and practice (instruments and singing) were selected to compute the musical experience score. These four questions were selected because they represent important factors that have a positive effect on auditory skills (Kraus & Chandrasekaran 2010). The selected questions were all Likert-scale type items (0 to 5) which respectively evaluate years of (1) instrument training, (2) instrument lessons, (3) singing training, and (4) singing lessons. The computed score was ranging from 0 (no musical training) to 20 (several decades of instrument and singing lessons and training). All participants with a score of 0 were assigned to the NM group (no musical experience; n = 39) because they reported no musical experience other than music classes they received in elementary and secondary school, which is part of the standard school curriculum in Quebec (Beatty 2007), and/or occasional singing (less than 5 years and no lessons). All other participants (n = 38) had scores ranging from 7 to 19 and were then assigned to the *M* group (with musical experience) because they all had some formal training (instrument or singing) and/or regularly played their instrument for at least 5 years. The number and types of instruments played, as well as the age of onset, years of practice, and education, have been reported for the *M* group (see Table 1 in Supplemental Digital Content, http://links.lww.com/EANDH/B538).

Hearing Loss Characterization • Participants underwent a complete audiometric screening including visualization of the external auditory canals with an otoscope, tympanometry (Tympani Inventis, s.r.l.), and pure-tone detection threshold measurements with a computer-controlled audiometer (Cello Diagnostic Audiometer, Inventis s.r.l.) in a soundproof booth with inserts earphones (RadioEar IP30). While PTA at 0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz were measured and included in

TABLE 1. Participant characteristics

	Without Musical Experience (n = 39)				With Musical Experience (n = 38)				
Characteristics	*M*	SD	Min	Max	*M*	SD	Min	Max	*t*(75)
Age	72.3	7.3	61	89	70.4	8.6	60	90	1.1
PTA	58.3	21.9	8.8	97.5	44.5	22.0	9.4	98.8	2.8*
Mus. Exp. Score (/20)	—	—	—	—	11.2	3.1	7	19	—
MoCA score (/30)	27.3	1.7	24	30	27.6	1.8	24	30	–1.6
GAI score (/20)	1.9	2.7	0	9	1.7	2.2	0	8	0.1
GDS score (/30)	3.1	2.8	0	10	3.0	2.9	0	10	0.0
	n		%		n		%		χ^2
Level of education									7.1*
Secondary	4		10		4		11		
College	14		36		4		11		
University	21		54		30		78		
Sex									1.1
Male	19		49		14		37		
Female	20		51		24		63		
Use of hearing aids†	19		49		6		16		9.5*

*$p < 0.05$.

†Number and percentage of participant answer "Yes" to the question "Do you wear hearing aids daily."

GAI, Geriatric Anxiety Inventory; GDS, Geriatric Depression Scale; M, mean; MoCA, Montreal Cognitive Assessment; Mus. Exp. Score, musical experience score based on the answers from the Edinburg Lifetime Musical Experience Questionnaire; PTA, pure-tone average (0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz); t(75), two-sided independent sample Student t-test with 75 degrees of freedom.

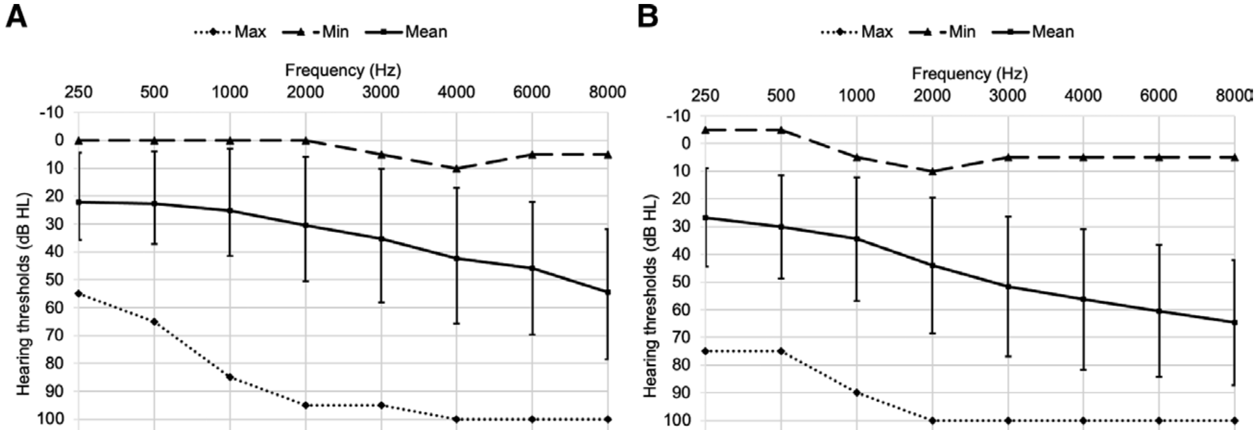

Fig. 1. Hearing thresholds (max, min, and mean). A, Group with musical experience. B, Group without musical experience. Error bars represent SD for each tested frequency.

participant characteristics (Table 1 and Fig. 1), only PTA at high frequencies was computed (PTA_{HF}: 3, 4, 5, 6, and 8 kHz) and used as hearing threshold representation for statistical analysis (analysis of covariance [ANCOVA] and regression analysis) because these frequencies are the ones at which hearing loss is the most frequent for older adults (International Organization for Standardization 2017). Out of the 46 individuals who reported no presbycusis, 34 (74%) of them had high-frequency hearing loss ranging from mild to moderately severe (Clark 1981) in at least one ear (PTA_{HF} >25 dB HL).

Rationale for Sample Size • Power analysis was conducted using G*Power 3.1.9.6 (Faul et al. 2009). For repeated measures of ANCOVA with two groups and two covariates, the minimal sample size required was calculated as N = 68 (34 per group), given a significance criterion of $\alpha = 0.05$, power of 0.90, and a large effect size of the independent variable on the dependent variable at $f = 0.40$. As for regression analysis, the minimal sample size was calculated at N = 54 (27 per group).

Procedure

Participants were seated comfortably in front of a 22-inch ACER computer screen plugged into an ASUS TUF Dash F15 Laptop running on Windows 11 Pro. Each music perception task was presented to the participants through over-ear headphones (Sennheiser HD 206) adjusted to each individual's comfortable sound level. The experiment has been adapted for use with a computer mouse (Logitech Wireless M185) using Gorilla Experiment Builder (Anwyl-Irvine et al. 2020) running on Google Chrome's latest version at the time (122.0.6261.39). To assess the natural hearing capabilities of all participants under the same listening conditions, those who wore hearing aids were asked to remove them, as not all participants with hearing loss were using amplification. Assessments and both tasks lasted a total of 90 min. To control for participant fatigue, we regularly checked with them before each task to see if they needed a break and allowed them to take one if necessary.

Montreal Battery for the Evaluation of Amusia • Selected tests from the MBEA (Peretz et al. 2003) were used to evaluate melodic and rhythm perception. Originally conceived as a screening tool for amusia (a music perception impairment), the MBEA has since been used commonly to assess general music perception abilities (Cooper et al. 2008; Hopyan et al. 2012; Moreno-Gómez et al. 2017). The MBEA is composed of three melodic organization tasks (scale, contour, and interval), two temporal organization tasks (rhythm and meter), and a music memory task. In our study, scale, contour, and rhythm subtasks were selected to assess melodic and rhythm perception. In music, scale refers to the tonal framework used, contour refers to pattern of ups and downs of a melody, and rhythm refers to temporal pattern of sounds and silences, organized in time (Peretz et al. 2003). Each subtask contains 30 sets of stimuli consisting of a warning tone, a target melody, and a comparison melody. Half of the comparison melodies have either one tone that is out of scale (scale condition), contour-violated (contour condition), or differs in duration value (rhythm condition) from the target melody. Participants had to judge whether the comparison melody was different or identical to the target melody (two-alternative forced choice) by selecting the corresponding answer using a computer mouse. No feedback was given. The three subtasks were presented in a predetermined sequence (Scale, contour, and rhythm) with the stimuli presented in a specific order within each subtask, in accordance with the standardized procedure outlined by Peretz et al. (2003). The entire process lasted approximately 25 min. These instrumental stimuli were produced by a digital synthesizer using a piano timbre. The mean duration of each set of stimuli was 16.7 sec. To ensure optimal listening conditions, two example trials with feedback were conducted before the task, allowing participants to indicate whether the stimuli were loud enough; the experimenter then adjusted the sound levels accordingly. A catch trial was also included to ensure they were paying close attention. The comparison melody for the catch trial was composed of randomly generated notes, making it sound decidedly distinct from all the comparison melodies. No participant failed the catch trial.

Instrument Discrimination Task • Modified sound samples from the Electronic Music Studio at the University of Iowa (Fritts 1997) were used for this task. There were 120 combinations of the following instruments: viola, cello, clarinet, alto saxophone, trombone, and trumpet. The first 0.5 sec of the stimuli were cut to remove acoustic information related to attack time. Then, only the following 1.5 sec of the stimuli was kept to remove acoustic information related to release time and to uniformize all stimuli duration to 1.5 sec, same as Russo et al. (2012). Furthermore, pitch and intensity for each stimulus were standardized to 440 Hz and 70 dB to remove cues related to frequency and amplitude fluctuations. Combinations ranged from easy (e.g., alto-clarinet) to difficult (e.g., viola-trumpet). The 120 combinations were presented in a randomized order and the total duration of the task was about 15 min. The mean duration of each combination was 6 sec. Participants had to select whether the stimuli were the same or different (two-alternative forced choice) by selecting the corresponding answer using a computer mouse. No feedback was given. Two example trials with feedback were conducted before the task, allowing participants to indicate whether the stimuli were loud enough; the experimenter then adjusted the sound levels accordingly. If participants failed the example trials, their results were excluded from the analyses. Two participants were excluded on this basis.

Statistical Analysis

Statistical analysis was conducted using IBM SPSS Statistics (version 29) running on Mac OS Sonoma. The hit rate (proportion of "different" responses when stimuli were different) and false alarm rate (proportion of "different" responses when stimuli were identical) for both the MBEA and instrument discrimination tasks were first computed and converted to *z*-scores using the inverse-normal transform $Z(x)$ to obtain d-prime values (Macmillan & Creelman 2004):

$$d' = Z(\text{Hit rate}) - Z(\text{False alarm rate})$$

D-prime is a measure of discriminability in signal detection theory (Stanislaw & Todorov 1999). A higher d-prime value indicates a better ability to detect a difference when one is present while a d-prime of 0 suggests no discrimination ability (VandenBos 2007). Because many participants had no false alarm or perfect hit detection rates, a correction was applied before calculating hit and false alarm rates by adding 0.5 to both the number of hits and of false alarms and adding 1 to the number of different (signal) and identical (noise) trials (Hautus 1995; Stanislaw & Todorov 1999).

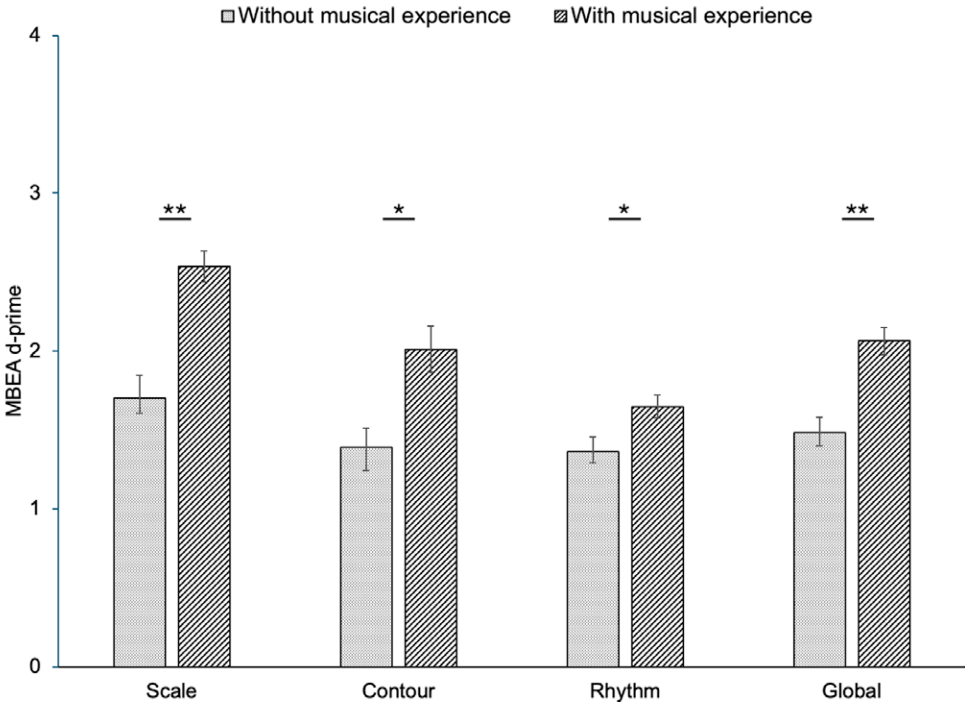

Fig. 2. Comparison of performance for the Montreal Battery of Evaluation of Amusia between groups for discriminability index (d-prime score). Error bars represent the mean SE. *$p < 0.05$, **$p < 0.001$ after Bonferroni correction.

For the MBEA task, an ANCOVA was used to evaluate the association between groups (NM, *M*) and discrimination accuracy (d-prime scores), with the subtasks (scale, contour, rhythm) included as within-subject effect to allow for comparison across them for both groups because they measure different abilities, as previously described in the Procedure. For the instrument discrimination task, an ANCOVA was also used to evaluate the association between groups (NM, *M*) and discrimination accuracy (d-prime scores), with each pair of instruments (alto-cello, alto-clarinet, alto-sax, alto-trumpet, alto-trombone, cello-clarinet, cello-sax, cello-trumpet, cello-trombone, clarinet-sax, clarinet-trumpet, clarinet-trombone, sax-trumpet, sax-trombone, trumpet-trombone) included as within-subject effect to allow for comparison across each instrument pairing for both groups. Both ANCOVA included age, hearing loss, level of education, and use of hearing aids as covariates and examined the interactions between age and hearing loss with groups. Post hoc *t* tests with Bonferroni correction were conducted to investigate which subtasks and pairs of instruments were significantly different between groups. Linear regression analyses within each group were also conducted to explore the association between significant covariates and the dependent variables. Finally, multiple regression analyses were conducted for both MBEA and instrument discrimination tasks in the *M* group to assess how the amount of musical experience correlates with d-prime scores of each task while controlling for age and hearing loss.

RESULTS

Montreal Battery Evaluation of Amusia

In the MBEA task, the musically experienced group (*M*) performed significantly better than the group without musical experience (NM), $F(1,69) = 12.699$, $p < 0.001$, controlling for age, hearing loss, level of education, and use of hearing aids (Fig. 2 and Table 2) with a large effect size ($\eta_p^2 = 0.184$). There was no significant effect of age, level of education, and use of hearing aids. The ANCOVA also revealed a significant interaction between the group effect and the subtasks, $F(2,69) = 3.791$, $p = 0.025$, with moderate effect size ($\eta_p^2 = 0.052$). Moreover, worse PTA_{HF} was related to lower d-prime score, $F(1,69) = 3.571$, $p = 0.040$, indicating a significant negative association between hearing loss severity and MBEA accuracy with a moderate effect size ($\eta_p^2 = 0.060$). However, this relationship was moderated by a significant interaction between hearing loss and group (Fig. 3), $F(1,69) = 4.326$, $p = 0.024$, with a moderate effect size ($\eta_p^2 = 0.071$). To further explore the interaction between group effect and the subtasks, post hoc *t* tests with Bonferroni correction were conducted to determine in which subtasks there were differences between the groups. Significant differences were observed between groups for the scale subtask ($p < 0.001$, Cohen $d = 1.105$) and contour subtask ($p = 0.011$, Cohen $d = 0.776$) with a large effect size, and for the rhythm subtask ($p = 0.038$, Cohen $d = 0.584$) with a moderate effect size (Fig. 2). Moreover, to investigate the significant interaction between hearing loss and group effect, post hoc multiple linear regression analyses were conducted within each group with MBEA global d-prime score as the dependent variable and with hearing loss and age as predictor variables. For the NM group, the regression model explained a significant amount of variance in MBEA scores, $F(2,36) = 6.843$, $p < 0.003$, adj. $R^2 = 0.235$, with hearing loss ($\beta = -0.013$, SE = 0.004, $p = 0.005$) being the main negative predictor of accuracy (Fig. 3 and Table 3). For the *M* group, the regression model was not significant, $F(3,35) = 1.596$, $p = 0.217$, adj. $R^2 = 0.031$, indicating no significant associations between MBEA accuracy and hearing loss or age for participants with musical experience (Fig. 3).

TABLE 2. Repeated measures ANCOVA for MBEA and Instrument discrimination tasks

Tasks	MBEA (Subtasks: Scale, Contour, Rhythm)				Instrument Discrimination (Subtasks: Instrument Pairings)			
Source	df	*F*	*p*	η^2_p	df	*F*	*p*	η^2_p
Within-subject effects								
Subtasks	2	3.911	0.022	0.054	11.512*	2.828*	0.001*	0.040*
Subtasks × Group	2	3.791	0.025	0.052	11.512*	1.829*	0.043*	0.027*
Between-subjects effects								
Group	1	15.589	<0.001	0.184	1	4.384	0.040	0.061
Age	1	2.345	0.130	0.033	1	2.257	0.138	0.033
Hearing loss	1	4.383	0.040	0.060	1	0.918	0.341	0.014
Education	1	1.684	0.199	0.024	1	1.038	0.312	0.015
Use of hearing aids	1	1.481	0.228	0.021	1	0.080	0.778	0.001
Group × Age	1	0.213	0.646	0.003	1	0.410	0.524	0.006
Group × Hearing Loss	1	5.310	0.024	0.071	1	0.075	0.785	0.001

**Huynh–Feldt epsilon corrections.*

ANCOVA, analysis of covariance; df, degree of freedom; MBEA, Montreal Battery Evaluation of Amusia; η^2_p, partial eta squared.

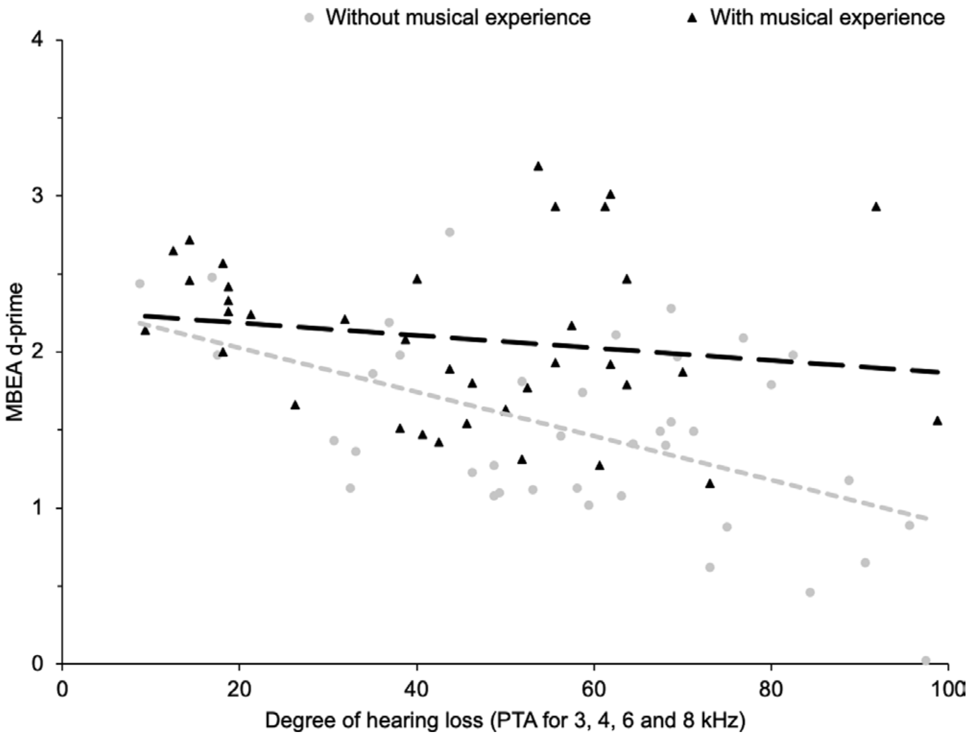

Fig. 3. Discriminability index (d-prime score) for global Montreal Battery Evaluation of Amusia task in participants without musical experience and with musical experience as a function of degree of hearing loss (PTA for 3, 4, 6, and 8 kHz). PTA indicates pure-tone average.

Instrument Discrimination Task

In the instrument discrimination task, Mauchly sphericity test revealed a violation of sphericity ($W = 0.007$, $p < 0.001$). Consequently, the Huynh–Feldt correction was applied to adjust the degrees of freedom for the within-subject effects. The *M* group performed significantly better than the NM group, $F(1,67) = 4.384$, $p = 0.040$, (Fig. 4A and Table 2) with a moderate effect size ($\eta_p^2 = 0.061$). Neither covariates nor interaction terms had significant effects on instrument discrimination accuracy. However, since a significant interaction between group effect and pairs of instruments was found, $F(11.512,771.308) = 1.829$, $p = 0.043$, with a small to moderate effect size ($\eta_p^2 = 0.027$), post hoc *t* tests with Bonferroni correction were conducted. D-prime scores for participants in the *M* group were significantly higher than those in NM group only for Viola-Cello ($p < 0.001$, Cohen $d = 0.906$) with a large effect size and Cello-Sax ($p = 0.050$, Cohen $d = 0.526$) with a moderate effect size (Fig. 4B).

Relation Between Amount of Musical Experience and Accuracy (*M* Group Only)

For the MBEA task, the predictive model including musical experience score, age, and hearing loss explained a significant amount of variance in MBEA d-prime score, $F(3,37) = 3.021$, $p = 0.043$, adj. $R^2 = 0.141$. Musical experience was found to be a main positive predictor ($\beta = 0.063$, SE $= 0.027$, $p = 0.025$), while neither hearing loss nor age were statistically significant

TABLE 3. Multiple linear regression analyses

Relation Between Hearing Loss and MBEA Global Accuracy Per Group												
	Without Musical Experience						With Musical Experience					
Groups	R	R^2	Adj. R^2	df	F	p	R	R^2	Adj. R^2	df	F	p
Regression model	0.525	0.275	0.235	2.36	6.843	0.003	0.289	0.084	0.031	2.35	1.596	0.217
Variable	B		SE	Beta (β)	t	p	B		SE	Beta (β)	t	p
(Constant)	2.778		0.861		3.227	0.003	3.358		0.768		4.370	<0.001
Age	−0.007		0.013	−0.091	−0.570	0.572	−0.018		0.012	0.288	−1.469	0.151
Hearing loss	−0.013		0.004	−0.477	−2.997	0.005	−6.593E-5		0.005	−0.003	−0.014	0.989

Relation Between Amount of Musical Experience and Accuracy (Musicians Only)												
	MBEA						Instrument Discrimination					
Tasks	R	R^2	Adj. R^2	df	F	p	R	R^2	Adj. R^2	df	F	p
Regression model	0.458	0.210	0.140	3.34	3.004	0.044	0.289	0.084	0.003	3.34	1.035	0.389
Variable	B		SE	Beta (β)	t	p	B		SE	Beta (β)	t	p
(Constant)	2.626		0.788		3.331	<0.001	2.996		0.633		4.733	<0.001
Mus. Exp. Score	0.063		0.027	0.370	2.338	0.025	0.015		0.022	0.118	0.694	0.492
Age	−0.019		0.012	−0.310	−1.681	0.102	−0.007		0.009	−0.148	−0.745	0.461
Hearing loss	−0.003		0.005	0.109	0.574	0.570	−0.002		0.004	−0.124	−0.607	0.548

B, unstandardized coefficient; Beta (β), standardized coefficient.

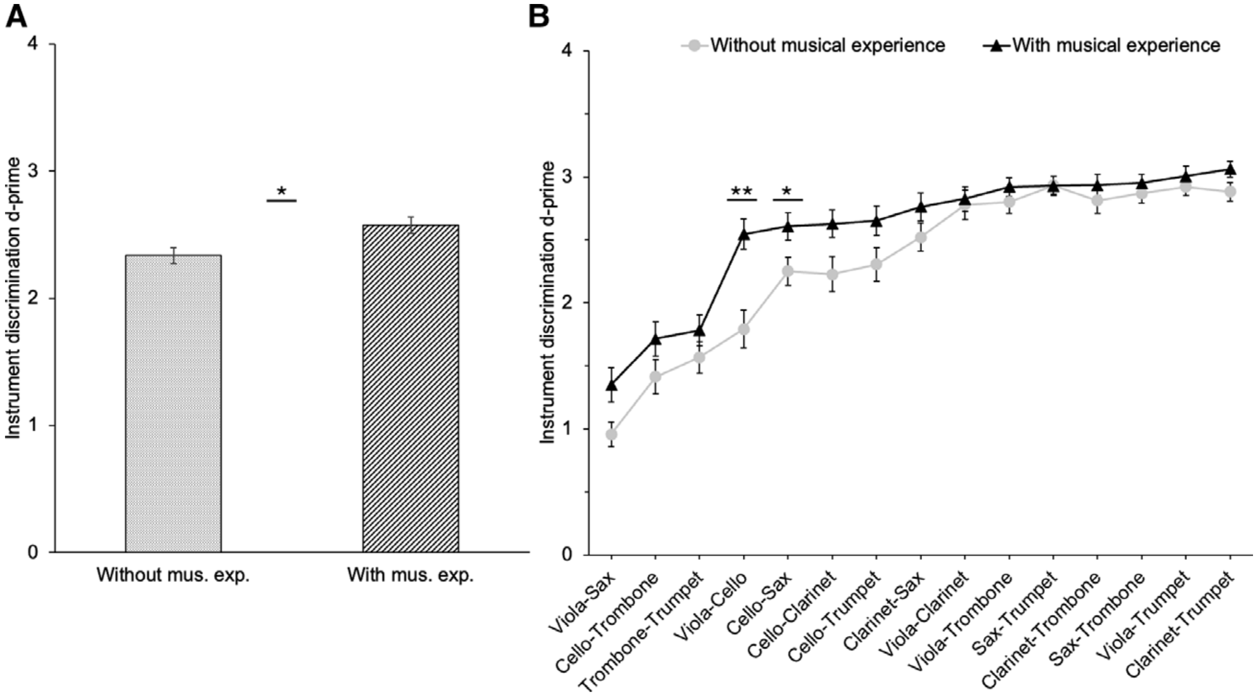

Fig. 4. A, Comparison of discriminability index (d-prime score) mean for instrument discrimination task between groups. Error bars represent the mean SE. B, Comparison of discriminability index (d-prime score) for each stimulus pair in instrument discrimination task between groups. *$p < 0.05$, **$p < 0.001$ after Bonferroni correction.

predictors (Table 3 and Fig. 5). For the instrument discrimination task, the regression model was not statistically significant, $F(3,34) = 1.035$, $p = 0.389$, adj. $R^2 = 0.003$ (Table 3), indicating that the amount of musical experience was not significantly correlated with accuracy for this task while neither age nor hearing loss explained variation for the dependent variable.

DISCUSSION

The main goal of the present study was to compare music perception abilities between adults aged 60 years or more with and without musical experience while controlling for the effect of age and hearing loss. Moreover, we explored how the amount of musical experience was associated with music perception abilities while controlling for age and hearing loss. We reported accuracy measures (d-prime scores) in tasks measuring melodic, rhythm, and timbre perception. On all tasks, musically experienced participants showed better accuracy than participants without musical experience while controlling for age and hearing loss. A moderate effect size was found for the instrument discrimination task measuring timbre perception while a large effect size was found for the tasks from the

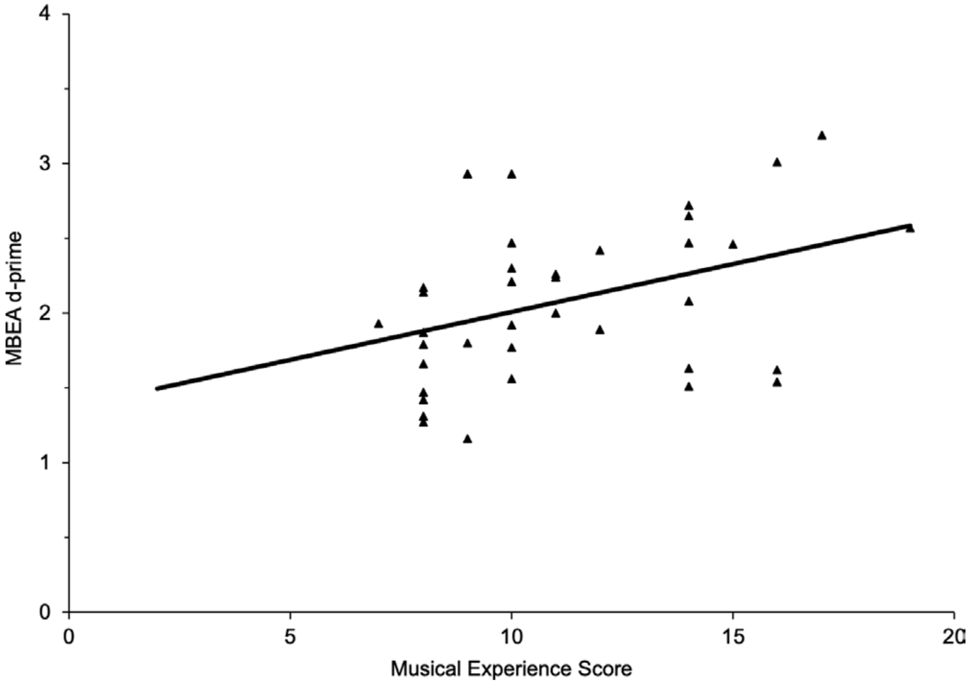

Fig. 5. Discriminability index (d-prime score) for global MBEA task in musical experience group as a function of musical experience score (only musical experience group). MBEA indicates Montreal Battery Evaluation of Amusia.

MBEA measuring melody and rhythm perception. The main effect of the MBEA subtasks (scale, contour, and rhythm) allowed us to observe significant differences between groups for each subtask, highlighting the distinct auditory processing abilities between musicians and nonmusicians. Our results are consistent with prior research, indicating that musical training is linked to a lower rate of deterioration of central auditory processing due to age and hearing loss. In line with principles of experience-dependent plasticity, it has been shown that musicians are better than nonmusicians at processing the pitch, temporal, and timbre components of music (Kraus & Chandrasekaran 2010). According to our results, older adults with musical experience maintain an advantage in these abilities despite age and hearing loss. Furthermore, musical experience mitigates the decline in melody and rhythm perception abilities associated with age-related hearing loss. This explanation aligns with findings from Zendel and Alain (2012) which showed that musicians experience less age-related decline in gap-detection and speech-in-noise detection tasks when compared with nonmusicians. Yet, despite being relevant to music perception, these auditory skills are not inherently music perception skills. Only a few studies to date have directly and specifically investigated music perception abilities in older adults with and without musical experience. Our study broadens existing literature by incorporating melodic (scale and contour), rhythm, and timbre perception tasks, which are essential in music listening and performance.

Impact of Musical Experience

Older adults with musical experience performed better than their nonmusically experienced counterparts for MBEA scale and contour subtasks when controlling for age and hearing loss. Both musical elements pertain to melodic perception. Scale refers to the key of the melody whilst contour is related to its direction (upward or downward movement) (Peretz et al. 2003). Our findings reveal that regardless of their age and degree of hearing loss, older individuals with musical experience are better than their nonmusically experienced counterparts at detecting subtle variations in scale and contour components of musical excerpts. It is well known that musically trained individuals perform better than nonmusicians in tests measuring the perception of variation within a melody such as the detection of an anomalous chord, mistuning detection or even determining how many notes are played in a chord (Schellenberg & Weiss 2013). Studies have shown that this advantage remains present in older musicians in melodic perception tasks measuring recognition of musical transpositions (Halpern et al. 1995) and representation of tonal hierarchies (Halpern et al. 1996). However, these studies were only conducted on normal-hearing older adults. In our research, we demonstrated that older adults with a varying degree of musical experience maintain superior melodic perception abilities even in the presence of presbycusis, because 76% (n = 28) of our sample of musically experienced individuals presented mild to severe hearing loss. These results are consistent with the findings reported by Moreno-Gómez et al. (2017), which showcased that music education (>1 year of music lessons) diminished the alterations observed in MBEA melodic tasks' (scale, contour, and interval) performance in Chilean older presbycusis patients. However, the limitations of this study include the use of a binary variable (yes/no) to characterize musical expertise, which oversimplifies the complexity of musical experience and lacks nuance. In addition, the audiometric threshold measurements were restricted to 0.25, 1, 2, and 4 kHz. Our study addresses this limitation by providing a more representative portrait of participant characteristics. We used a high-frequency PTA (PTA_{HF}) that better represents presbycusis including 3, 4, 6, and 8 kHz, which are frequencies most affected by age-related hearing loss. We also included a musical experience score derived from a standardized questionnaire. Finally, although we controlled for the degree of hearing loss in each analysis, an intriguing finding related to musicians' characteristics is supported by previous studies: musicians had lower PTA scores compared with nonmusicians. Some studies indicate that musicians tend to excel in pure-tone audiometry threshold measurements due to their familiarity with identifying pure tones, which is a result of auditory training and task-specific experience, as well as their strong motivation to succeed in such tasks (Dowling & Harwood 1987; Jansen et al. 2009). Overall, these results add to existing knowledge by showcasing that even in older people with varying ages and degrees of hearing loss, musical experience helps maintain their enhanced melodic perception abilities compared with individuals without musical experience.

In the case of rhythm perception, a group difference was also observed for the measure of discriminability in the rhythm subtask from the MBEA. Rhythm is a component of temporal organization in music perception which corresponds to the tendency to organize events based on their temporal proximity without regard to periodicity (Peretz et al. 2003). Individuals with musical experience showed significantly higher discriminability index than participants without musical experience, thus showing a better ability to detect rhythm differences in musical excerpts. Temporal processing in musicians has been extensively examined over the years. Several studies have shown that musicians are better than nonmusicians in gap-detection (Mohamadkhani et al. 2010; Zendel & Alain 2012; Kumar et al. 2014; Nisha et al. 2022), duration discrimination (Rammsayer & Altenmüller 2006; Güçlü et al. 2011; Kumar et al. 2014; Grassi et al. 2017) and temporal patterns discrimination (Rammsayer & Altenmüller 2006) tasks. Conversely, it has been shown that temporal processing abilities decline with age (Zendel et Alain 2012; Fitzgibbons & Gordon-Salant 2015; Ozmeral et al. 2016; Carcagno & Plack 2021) and hearing loss (John et al 2012; Moreno-Gómez et al. 2017). Despite this decline, Halpern et al. (1998) have shown that older musicians perform better than their nonmusician counterparts in tasks involving the detection of rhythm variations between two melodies. However, once again, the sample from this study included only normal-hearing individuals. Our study addresses this limitation by showing that older adults with musical experience maintain this benefit in rhythm perception over individuals without musical experience despite deteriorations due to aging and hearing loss. Because playing an instrument requires acute rhythm management, it is expected that music training improves the ability to detect rhythmic variations in music-related stimuli. Our results not only support this hypothesis, but also reveal that musically experienced individuals keep their enhanced rhythm perception despite their age-related hearing loss.

For the instrument discrimination task measuring timbre perception, participants with musical experience had significantly higher global measure of discriminability than participants without musical experience when controlling for age and hearing loss. Timbre is a complex perceptual attribute resulting from a combination of temporal, spectral, and spectro-temporal envelopes (Marozeau et al. 2013; McAdams & Giordano 2016) that contributes to the unique quality or color of an instrument's tone. It is a key factor that allows different instruments to be distinguished even when they play the same note, for the same length, and at the same intensity. In our study, musically experienced older adults outperformed participants without musical experience of the same age in distinguishing instrument stimuli based on their timbre characteristics. Because of its central role in music, it is expected that experienced musicians performed better than nonmusicians in discriminating timbre. Pitt (1994) reported that musicians showed enhanced performance compared with nonmusicians in a task involving the detection of pitch or timbre changes in piano and trumpet stimuli. Chartrand and Belin (2006) documented that musicians were more accurate and faster than controls in a timbre discrimination task involving instrument and voice stimuli. However, these studies explored timbre perception only in normal-hearing adults. Indeed, because of its complex nature, timbre has not been extensively explored in the older adults, especially not in those with presbycusis. Our study addresses this gap in the literature by suggesting that this advantage present in musically experienced individuals persists even as they get older and despite presbycusis. More specifically, we found that significant differences between groups were observed for two pairs of instruments (viola-cello and cello-sax), which appear to be of intermediate difficulty for participants according to the psychometric plot. No differences between groups were found for the easier pairs (viola-clarinet, viola-trombone, sax-trumpet, clarinet-trombone, sax-trombone, viola-trumpet, and clarinet-trumpet), where a ceiling effect was observed. These results are in line with previous studies that have shown that even adults without musical training can be very sensitive to the perception of subtle timbre differences in digital tones (Samson et al. 1997) and instrument stimuli (Peynircioğlu et al. 2015). Moreover, the more difficult instrument (viola-sax, cello-trombone, and trombone-trumpet) pairs were equally challenging for both groups. Further investigation should explore the use of other intermediate pairs of instruments because this difficulty degree seems to be the most sensitive to differences between participants with and without musical experience. In the selected stimuli, acoustic information related to attack and release time was removed while pitch, duration, and intensity were controlled for each stimulus. This was done to standardize each stimulus so that they would be distinguished by their spectral component. However, even if these acoustic traits were controlled, timbre perception is related to multiple spectral elements that were not controlled (centroid, spread, kurtosis, odd-to-even ratio, etc.). With the current paradigm, it is difficult to identify which of these acoustic traits have a more predominant role in the measured instrument discrimination performance. Further investigations are required to identify which spectral acoustic traits make it easier or more difficult to distinguish instruments between each other and how perception of these traits is influenced by musical experience, age, and hearing loss. Moreover, familiarity with the instruments used for comparison has not been investigated in the present study, which would be an interesting avenue to investigate from an experience-driven perspective. Because only 3 participants from the musicians' group had one of the instruments presented in the excerpts of the instrument detection task as their primary instrument, it was not possible to draw conclusions about how familiarity with these instruments influenced their performance. Moreover, these participants were multi-instrumentalists, which is common in Québec, where most music education programs encourage the study of multiple instruments. To explore the impact of familiarity with the instruments found among the excerpts, future research could recruit a larger sample of musicians who play these instruments and analyze the relationship between the instruments they play and their scores on the instrument pairings task. Alternatively, the task could be modulated by varying the instrument pairs to include congruent and incongruent stimuli related to each musician's primary instrument. These investigations could provide valuable insights into how familiarity influences performance in the detection task. A task featuring a continuum from lesser known to well-known instruments could provide valuable insights into the impact of familiarity with instruments on performance. However, it is important to acknowledge that despite all these avenues of research that remain to be explored, the task demonstrated sufficient sensitivity to detect a global significant difference between older adults with and without musical experience. Hence, our results show that experience-induced enhancement in timbre perception remains present in musically experienced individuals even as their auditory processing deteriorates with age.

Impact of Hearing Loss and Amount of Musical Experience

Our second objective was to assess the impact of age, hearing loss, and amount of musical experience on accuracy for MBEA and instrument discrimination tasks. For the MBEA task, hearing loss was found to be the main predictor of global accuracy in older adults without musical experience, indicating a negative association between hearing loss with melody and rhythm perception abilities, while controlling for age. This relation was expected since past studies have reported similar negative relationships between hearing impairment in hard-of-hearing older adults and music perception (Hake et al. 2023), speech perception (Cox et al. 2008; Peixe et al. 2019), and temporal resolution (John et al. 2012). In musically experienced individuals, the amount of musical experience appeared to be the main predictor of global accuracy for the MBEA task while controlling for age and hearing loss. Similar results were reported by Moreno-Gómez et al. (2017) revealing that music training significantly correlates with overall MBEA performance in individuals aged 64 and older, even when accounting for age-related hearing loss. Overall, these results imply that despite the alteration of melodic and rhythm perception in older adults with hearing loss, musical experience is associated with a less marked deterioration in these abilities. Furthermore, even when controlling for age and hearing loss, more musical experience (years of training and practice) is significantly linked to better melody and rhythm perception skills. In other words, the more years of training and practice one gets, the more likely it is that their melodic and rhythm perception abilities will not be as deteriorated as someone without musical experience at old age. For the instrument discrimination task, none of our predictors (age, hearing loss, and/or musical experience) could explain the variance in d-prime score for both groups. This could be due to the ceiling effect which hindered the analysis from identifying a model that significantly predicts accuracy. Overall, our results demonstrate that older adults with musical experience exhibit significantly better music perception abilities compared with those without such experience, regardless of their age or hearing loss. Furthermore, we found that the amount of musical experience correlates with enhanced melody and rhythm perception abilities. In contrast, hearing loss in nonmusically experienced individuals reduces their ability to accurately perceive melody and rhythm in musical stimuli. Finally, our study suggests the rather pivotal idea that musical experience moderates the negative impact of hearing loss on melody and rhythm perception.

Perspective

These findings allowed us to demonstrate that, even in the context of age-related hearing loss, there is a long-term correlation between improved musical perception abilities and musical experience. It should be noted that while our tasks measured melody, rhythm, and timbre perception, our stimuli may not faithfully replicate real-world music conditions. Music compositions typically involve greater complexity than the short piano excerpts and single-tone instrument samples utilized in our study, thereby limiting its ecological validity. Further investigation should include subjective assessment of music perception and appreciation to gather more information on how participants perceive different styles of music despite their presbycusis. Moreover, while it has been suggested that better innate characteristics in overall music perception, including melody, rhythm, and timbre perception, could be linked to involvement in musical pursuits (McKay 2021), the cross-sectional design of this study only provides a snapshot in time. As such, it does not allow for assessments of changes over time and this inability to establish temporal precedence limits the possibility to draw causal conclusions. Further studies should consider longitudinal randomized controlled designs to establish potential causal relationships. For example, music lessons given over a period could be an interesting avenue to explore its impact on melodic, rhythm, and timbre perception in older adults with hearing impairment. Furthermore, while much evidence suggests that age of onset can enhance musical skills and modulate training-driven brain plasticity (Bailey & Penhune 2012; Bailey et al. 2014), the relationship between age of onset and musical proficiency in adulthood remains a subject of ongoing debate (Wesseldijk et al. 2020). Future studies should investigate the nuanced effects of age of onset in relation to the intensity and consistency of musical training, particularly in how these factors interact with age-related hearing loss and the decline of central auditory abilities. Nevertheless, because perception of melody, rhythm, and timbre is essential to fully perceive and appreciate music, our results are very promising from a rehabilitation perspective. Given that listening to music is such an important leisure activity with many benefits (Coffman 2002; Hays et al 2002; Laukka 2007; Solé et al. 2010; MacDonald 2013; Fung & Lehmberg 2016; Daykin et al. 2018; Castillejos & Godoy-Izquierdo 2021), it is essential that older adults can enjoy it just as much as other age groups. Considering current results, the next step would be to explore whether musical training started at an advanced age would restore musical perception skills degraded by age and hearing loss. Improving these skills could allow older adults who have not had the opportunity to play music in their lives to enjoy the same benefits of music that individuals with musical experience can appreciate, despite their presbycusis.

CONCLUSIONS

The objective of this study was to investigate the impact of musical experience on the following music perception abilities: melody, rhythm, and timbre perception. The impact of age and hearing loss on these abilities was also observed for each group to see if the age-related decline in these abilities is solely attributable to presbycusis. Musically experienced individuals performed better than participants without musical experience for all three tasks when controlling for age and hearing loss. These results are consistent with prior studies showcasing that musicianship is associated with better music perception abilities. The amount of musical experience predicted better accuracy, while hearing loss predicted significant decline for older adults without musical experience in melodic and rhythm perception tasks. These results further enhance the notion that music training is beneficial and acts as a protective factor on the impact of presbycusis in central auditory processing abilities. While more research is needed, because we observe a positive association between musical experience and music perception abilities, music training could be a creative and effective approach to improve music perception abilities in hard-of-hearing older adults, thereby improving their music listening experience and its many benefits.

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A.S., P.T., and I.B. acquired funding and conceptualized the project. A.S., P.T., I.B., L.C., and A.W. contributed to the development and implementation of the methodology. A.S. administered the project and provided resources. A.W. and A.B. collected data. A.S. and A.W. curated, analyzed data, and wrote the manuscript. P.T. and I.B. provided statistical guidance and critical revision. All authors discussed the results, implications, and commented on the manuscript.

The Research Committee for sectorial research in neuroscience and mental health of the CIUSSS—Capitale Nationale approved all procedures (Project 2023-2683 submitted by the principal investigator, Andreanne Sharp) and each participant provided written informed consent. All experiments were performed in accordance with relevant guidelines and regulations.

The authors have no conflicts of interest to disclose.

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REFERENCES

Anwyl-Irvine, A. L., Massonnié, J., Flitton, A., Kirkham, N., Evershed, J. K. (2020). Gorilla in our midst: An online behavioral experiment builder. *Behav Res Methods*, *52*, 388–407.

Bailey, J., & Penhune, V. B. (2012). A sensitive period for musical training: Contributions of age of onset and cognitive abilities. *Ann N Y Acad Sci*, *1252*, 163–170.

Bailey, J. A., Zatorre, R. J., Penhune, V. B. (2014). Early musical training is linked to gray matter structure in the ventral premotor cortex and auditory–motor rhythm synchronization performance. *J Cogn Neurosci*, *26*, 755–767.

Beatty, R. J. (2007). The history and development of elementary music education in Canada–Curricular perspectives. In K. Veblen, C. Beynon, S. Horsley, U. DeAlwiss, A. Heywood (Eds.), *From Sea to Sea: Perspectives on Music Education in Canada*. Western Libraries, The University of Western Ontario. https://ir.lib.uwo.ca/musiceducationebooks/1.

Bones, O., & Plack, C. J. (2015). Losing the music: Aging affects the perception and subcortical neural representation of musical harmony. *J Neurosci*, *35*, 4071–4080.

Bourque, P., Blanchard, L., Vézina, J. (1990). Étude psychométrique de l'Échelle de dépression gériatrique. *Can J Aging*, *9*, 348–355.

Carcagno, S., & Plack, C. J. (2021). Effects of age on psychophysical measures of auditory temporal processing and speech reception at low and high levels. *Hear Res*, *400*, 108117.

Carson, N., Leach, L., Murphy, K. J. (2018). A re-examination of Montreal Cognitive Assessment (MoCA) cutoff scores. *Int J Geriatr Psychiatry*, *33*, 379–388.

Castillejos, C., & Godoy-Izquierdo, D. (2021). "Music makes my old heart beat": A randomised controlled study on the benefits of the use of music in comprehensive care for institutionalised older adults. *Appl Psychol Health Well Being*, *13*, 84–108.

Champagne, A., Landreville, P., Gosselin, P., Carmichael, P. H. (2018). Psychometric properties of the French Canadian version of the Geriatric Anxiety Inventory. *Aging Ment Health*, *22*, 40–45.

Chartrand, J. P., & Belin, P. (2006). Superior voice timbre processing in musicians. *Neurosci Lett*, *405*, 164–167.

Chern, A., Denham, M. W., Leiderman, A. S., Sharma, R. K., Su, I. W., Ucci, A. J., Jones, J. M., Mancuso, D., Cellum, I. P., Galatioto, J. A., Lalwani, A. K. (2023). The association of hearing loss with active music enjoyment in hearing aid users. *Otolaryngol Head Neck Surg*, *169*, 1590–1596.

Clark, J. G. (1981). Uses and abuses of hearing loss classification. *ASHA*, *23*, 493–500.

Clinard, C. G., Tremblay, K. L., Krishnan, A. R. (2010). Aging alters the perception and physiological representation of frequency: Evidence from human frequency-following response recordings. *Hear Res*, *264*, 48–55.

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

Coffman, D. D. (2002). Music and quality of life in older adults. *Psychomusicology*, *18*, 76–88.

Cooper, W. B., Tobey, E., Loizou, P. C. (2008). Music perception by cochlear implant and normal hearing listeners as measured by the Montreal Battery for Evaluation of Amusia. *Ear Hear*, *29*, 618–626.

Cox, C. L., McCoy, S. L., Tun, P. A., Wingfield, A. (2008). Monotic auditory processing disorder tests in the older adult population. *J Am Acad Audiol*, *19*, 293–308.

Croom, A. M. (2015). Music practice and participation for psychological well-being: A review of how music influences positive emotion, engagement, relationships, meaning, and accomplishment. *Music Sci*, *19*, 44–64.

Daykin, N., Mansfield, L., Meads, C., Julier, G., Tomlinson, A., Payne, A., Grigsby Duffy, L., Lane, J., D'Innocenzo, G., Burnett, A., Kay, T., Dolan, P., Testoni, S., Victor, C. (2018). What works for wellbeing? A systematic review of wellbeing outcomes for music and singing in adults. *Perspect Public Health*, *138*, 39–46.

Dingle, G. A., Sharman, L. S., Bauer, Z., Beckman, E., Broughton, M., Bunzli, E., Davidson, R., Draper, G., Fairley, S., Farrell, C., Flynn, L. M., Gomersall, S., Hong, M., Larwood, J., Lee, C., Lee, J., Nitschinsk, L., Peluso, N., Reedman, S. E., Wright, O. R. L. (2021). How do music activities affect health and well-being? A scoping review of studies examining psychosocial mechanisms. *Front Psychol*, *12*, 713818.

Dowling, W. J., & Harwood, D. L. (1987). Music cognition. *Psychomusicology*, *7*, 91.

Faul, F., Erdfelder, E., Buchner, A., Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behav Res Methods*, *41*, 1149–1160.

Fitzgibbons, P. J., & Gordon-Salant, S. (2015). Age effects in discrimination of intervals within rhythmic tone sequences. *J Acoust Soc Am*, *137*, 388–396.

Fritts, L. (1997). *Musical instrument samples*. The University of Iowa Electronic Music Studios [Online]. http://theremin.music.uiowa.edu/index.html.

Fung, C. V., & Lehmberg, L. J. (2016). *Music for Life: Music Participation and Quality of Life of Senior Citizens*. Oxford University Press.

Gates, G. A., & Mills, J. H. (2005). Presbycusis. *Lancet*, *366*, 1111–1120.

Granot, R., Spitz, D. H., Cherki, B. R., Loui, P., Timmers, R., Schaefer, R. S., Vuoskoski, J. K., Cárdenas-Soler, R. N., Soares-Quadros, J. F., Li, S., Lega, C., la Rocca, S., Martínez, I. C., Tanco, M., Marchiano, M., Martínez-Castilla, P., Pérez-Acosta, G., Martínez-Ezquerro, J. D., Gutiérrez-Blasco, I. M., Israel, S. (2021). "Help! I need somebody": Music as a global resource for obtaining wellbeing goals in times of crisis. *Front Psychol*, *12*, 648013.

Grassi, M., Meneghetti, C., Toffalini, E., Borella, E. (2017). Auditory and cognitive performance in elderly musicians and nonmusicians. *PLoS One*, *12*, e0187881.

Greasley, A., Crook, H., Fulford, R. (2020). Music listening and hearing aids: Perspectives from audiologists and their patients. *Int J Audiol*, *59*, 694–706.

Grenier, A. S., Lafontaine, L., Sharp, A. (2021). Use of music therapy as an audiological rehabilitation tool in the elderly population: A mini-review. *Front Neurosci*, *15*, 662087.

Güçlü, B., Sevinc, E., Canbeyli, R. (2011). Duration discrimination by musicians and nonmusicians. *Psychol Rep*, *108*, 675–687.

Hake, R., Bürgel, M., Nguyen, N. K., Greasley, A., Müllensiefen, D., Siedenburg, K. (2023). Development of an adaptive test of musical scene analysis abilities for normal-hearing and hearing-impaired listeners. *Behav Res Methods*, *56*, 5456–5481.

Halpern, A. R., Bartlett, J. C., Dowling, W. J. (1995). Aging and experience in the recognition of musical transpositions. *Psychol Aging*, *10*, 325–342.

Halpern, A. R., Bartlett, J. C., Dowling, W. J. (1998). Perception of mode, rhythm, and contour in unfamiliar melodies: Perception of mode, rhythm, and contour in unfamiliar melodies: Effects of age and experience effects of age and experience. *Commons Bucknell digital commons faculty journal articles faculty scholarship*. http://www.jstor.org/stable/40300862.

Halpern, A. R., Kwak, S., Bartlett, J. C., Dowling, W. J. (1996). Effects of aging and musical experience on the representation of tonal hierarchies. *Psychol Aging*, *11*, 235–246.

Hautus, M. J. (1995). Corrections for extreme proportions and their biasing effects on estimated values of d′. *Behav Res Methods Instrum Comput*, *27*, 46–51.

Hays, T., Bright, R., Minichiello, V. (2002). The contribution of music to positive aging: A review. *J Aging Identity*, *7*, 165–175.

Hopyan, T., Peretz, I., Chan, L. P., Papsin, B. C., Gordon, K. A. (2012). Children using cochlear implants capitalize on acoustical hearing for music perception. *Front Psychol*, *3*, 32749.

International Organization for Standardization. (2017). *Acoustics—Statistical distribution of hearing thresholds related to age and gender (ISO Standard No. 7029:2017)*. https://www.iso.org/standard/42916.html.

Jansen, E. J. M., Helleman, H. W., Dreschler, W. A., De Laat, J. A. P. M. (2009). Noise induced hearing loss and other hearing complaints among musicians of symphony orchestras. *Int Arch Occup Environ Health*, *82*, 153–164.

John, A. B., Hall, J. W., Kreisman, B. M. (2012). Effects of advancing age and hearing loss on gaps-in-noise test performance. *Am J Audiol*, *21*, 242–250.

Kraus, N., & Chandrasekaran, B. (2010). Music training for the development of auditory skills. *Nat Rev Neurosci*, *11*, 599–605.

Kumar, P. V., Rana, B., Krishna, R. (2014). Temporal processing in musicians and non-musicians. *J Hear Sci*, *4*, 35–42.

Larouche, E., Tremblay, M. P., Potvin, O., Laforest, S., Bergeron, D., Laforce, R., Hudon, C. (2016). Normative data for the Montreal Cognitive Assessment in middle-aged and elderly Quebec-French people. *Arch Clin Neuropsychol*, *31*, 819–826.

Laukka, P. (2007). Uses of music and psychological well-being among the elderly. *J Happiness Stud*, *8*, 215–241.

Leek, M. R., Molis, M. R., Kubli, L. R., Tufts, J. B. (2008). Enjoyment of music by elderly hearing-impaired listeners. *J Am Acad Audiol*, *19*, 519–526.

Looi, V., Rutledge, K., Prvan, T. (2019). Music appreciation of adult hearing aid users and the impact of different levels of hearing loss. *Ear Hear*, *40*, 529–544.

Lv, H., Gao, Z., Wang, Y., Xie, Y., Guan, M., Liao, H., Xu, Y. (2023). Global characteristics and trends of presbycusis research from 2002 to 2021: A bibliometric study. *Am J Transl Res*, *15*, 2407–2425.

MacDonald, R. A. (2013). Music, health, and well-being: A review. *Int J Qual Stud Health Well-being*, *8*, 20635.

Macmillan, N. A., & Creelman, C. D. (2004). *Detection Theory: A User's Guide* (2nd ed.). Psychology Press. https://doi.org/10.4324/9781410611147.

Maillard, E., Joyal, M., Murray, M. M., Tremblay, P. (2023). Are musical activities associated with enhanced speech perception in noise in adults? A systematic review and meta-analysis. *Curr Res Neurobiol*, *4*, 100083.

Marozeau, J., Innes-Brown, H., Blamey, P. J. (2013). The effect of timbre and loudness on melody segregation. *Music Percept*, *30*, 259–274.

McAdams, S., & Giordano, B. L. (2016). The perception of musical timbre. In S. Hallam, I. Cross, M. Thaut (Eds.), *The Oxford Handbook of Music Psychology* (2nd ed.). Oxford Handbooks Online. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780198722946.013.12.

McKay, C. M. (2021). No evidence that music training benefits speech perception in hearing-impaired listeners: A systematic review. *Trends Hear*, *25*, 233121652098567.

Mohamadkhani, G., Nilforoushkhoshk, M. H., Zadeh Mohammadi, A., Faghihzadeh, S., Sepehrnejhad, M. (2010). Comparison of gap in noise test results in musicians and non-musician controls. *Audiology*, *19*, 33–38.

Moore, B. C. (1996). Perceptual consequences of cochlear hearing loss and their implications for the design of hearing aids. *Ear Hear*, *17*, 133–161.

Moore, B. C. (2007). Prevalence of dead regions in subjects with sensorineural hearing loss. *Ear Hear*, *28*, 231–241.

Moreno-Gómez, F. N., Véliz, G., Rojas, M., Martínez, C., Olmedo, R., Panussis, F., Delano, P. H. (2017). Music training and education slow the deterioration of music perception produced by presbycusis in the elderly. *Front Aging Neurosci*, *9*, 149.

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. *J Am Geriatr Soc*, *53*, 695–699.

Nisha, K. V., Durai, R., Konadath, S. (2022). Musical training and its association with age-related changes in binaural, temporal, and spatial processing. *Am J Audiol*, *31*, 669–683.

Okely, J. A., Deary, I. J., Overy, K. (2021). The Edinburgh Lifetime Musical Experience Questionnaire (ELMEQ): Responses and non-musical correlates in the Lothian Birth Cohort 1936. *PLoS One*, *16*, e0254176.

Ozmeral, E. J., Eddins, A. C., Frisina, D. R., Sr, Eddins, D. A. (2016). Large cross-sectional study of presbycusis reveals rapid progressive decline in auditory temporal acuity. *Neurobiol Aging*, *43*, 72–78.

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*, e18082.

Peixe, B. P., Sanguebuche, T. R., Malavolta, V. C., Garcia, M. V. (2019). The study of responses to auditory processing tests in the elderly. *Rev CEFAC*, *21*(6). https://doi.org/10.1590/1982-0216/201921613818.

Peretz, I., Champod, A. S., Hyde, K. (2003). Varieties of musical disorders: The Montreal Battery of Evaluation of Amusia. *Ann N Y Acad Sci*, *999*, 58–75.

Peynircioğlu, Z. F., Brent, W., Falco, D. E. (2015). Perception of blended timbres in music. *Psychol Music*, *44*, 625–639.

Pitt, M. A. (1994). Perception of pitch and timbre by musically trained and untrained listeners. *J Exp Psychol Hum Percept Perform*, *20*, 976–986.

Rammsayer, T., & Altenmüller, E. (2006). Temporal information processing in musicians and nonmusicians. *Music Percept*, *24*, 37–48.

Russo, F. A., Ammirante, P., Fels, D. I. (2012). Vibrotactile discrimination of musical timbre. *J Exp Psychol Hum Percept Perform*, *38*, 822–826.

Samson, S., Zatorre, R. J., Ramsay, J. O. (1997). Multidimensional scaling of synthetic musical timbre: Perception of spectral and temporal characteristics. *Can J Exp Psychol*, *51*, 307–315.

Schellenberg, E. G., & Weiss, M. W. (2013). Music and cognitive abilities. In D. Deutsch (Ed.), *The Psychology of Music* (3rd ed., pp. 499–550). Academic Press.

Solé, C., Mercadal-Brotons, M., Gallego, S., Riera, M. (2010). Contributions of music to aging adults' quality of life. *J Music Ther*, *47*, 264–281.

Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behav Res Methods Instrum Comput*, *31*, 137–149.

VandenBos, G. R. (2007). *APA Dictionary of Psychology*. American Psychological Association. https://dictionary.apa.org/d-prime.

Wallin, N. L., Merker, B., Brown, S. (Eds.). (1999). *The Origins of Music*. The MIT Press. https://doi.org/10.7551/mitpress/5190.001.0001.

Welch, G. F., Biasutti, M., MacRitchie, J., McPherson, G. E., Himonides, E. (2020). The impact of music on human development and well-being. *Front Psychol*, *11*, 1246.

Wesseldijk, L. W., Mosing, M. A., Ullén, F. (2020). Why is an early start of training related to musical skills in adulthood? A genetically informative study. *Psychol Sci*, *32*, 3–13.

World Health Organization. (2021). *World Report on Hearing*. https://www.who.int/publications/i/item/world-report-on-hearing.

Yamasoba, T., Lin, F. R., Someya, S., Kashio, A., Sakamoto, T., Kondo, K. (2013). Current concepts in age-related hearing loss: Epidemiology and mechanistic pathways. *Hear Res*, *303*, 30–38.

Zendel, B. R., & Alain, C. (2012). Musicians experience less age-related decline in central auditory processing. *Psychol Aging*, *27*, 410–417.

Zendel, B. R., West, G. L., Belleville, S., Peretz, I. (2019). Musical training improves the ability to understand speech-in-noise in older adults. *Neurobiol Aging*, *81*, 102–115.

Zhang, L., Fu, X., Luo, D., Xing, L., Du, Y. (2021). Musical experience offsets age-related decline in understanding speech-in-noise: Type of training does not matter, working memory is the key. *Ear Hear*, *42*, 258–270.